CANS

– Compact Accelerator-driven Neutron Sources

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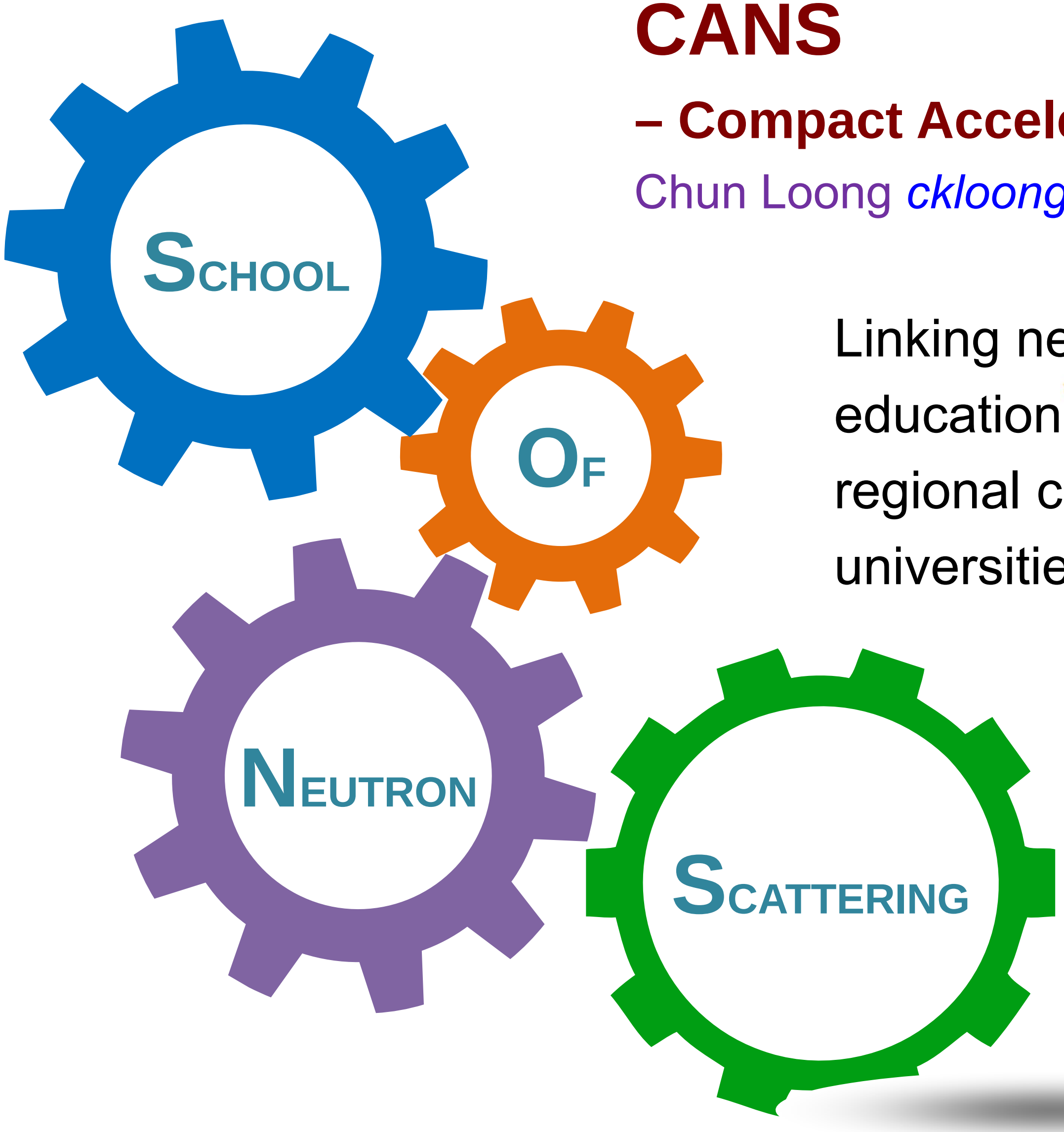


Linking neutron applications – R&D and education – among international projects, regional centers, government labs, universities, & industry

28 July – 4 August, 2015 ENCSC-Erice

Outline

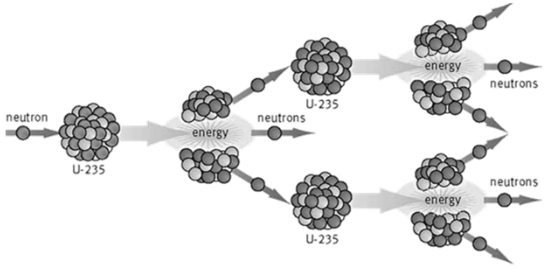
1 An Overview
  - ✧ CANS: What they are and how they play a role in the neutron S&T
  - ✧ The community: *The Union for Compact Accelerator-driven Neutron Sources* (***UCANS***)
  - ✧ Facilities currently in operation or under development

2 The CANS accelerator structure
  - ✧ Cost-effectiveness
  - ✧ An ideal front-end for supporting neutron instrumentation R&D and user training

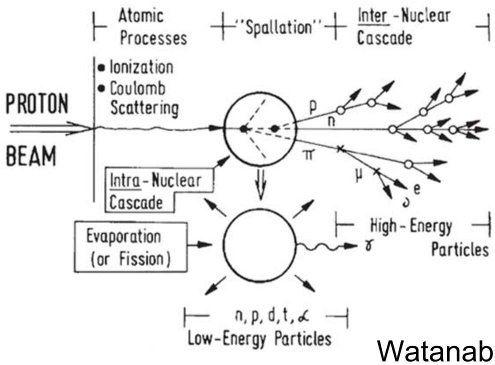
3 Applications
  - ✧ The multidisciplinary nature and diverse utilization

Neutron Production Mechanisms

Reactions	Neutron Production Examples
Fission	${}^{235}U + n \longrightarrow A^* + B^* + xn; \quad \langle x \rangle \sim 2.5$
Spallation	$p + {}^{184}W \longrightarrow A^* + B^* + xn, \quad \langle x \rangle \sim 20$
Fusion	$d + t \longrightarrow \alpha(3.5MeV) + n(14.1MeV)$ $d + d \longrightarrow \alpha(0.866MeV) + n(2.4MeV)$
Photoproduction	$\gamma + {}^{181}Ta \longrightarrow {}^{180}Ta + n$, ©+ ${}^{2}H \longrightarrow {}^{1}H + n$
Charged-particle reaction	${}^{9}Be + p \longrightarrow {}^{9}B + n$, ${}^{2}H + {}^{3}H \longrightarrow {}^{3}He + n$
(n,xn)	${}^{9}Be + n \longrightarrow {}^{8}B^* + 2n$
Excited-state decay	${}^{13}C^{**} \longrightarrow {}^{12}C^* + n$, ${}^{130}Sn^{**} \longrightarrow {}^{129}Sn^* + n$

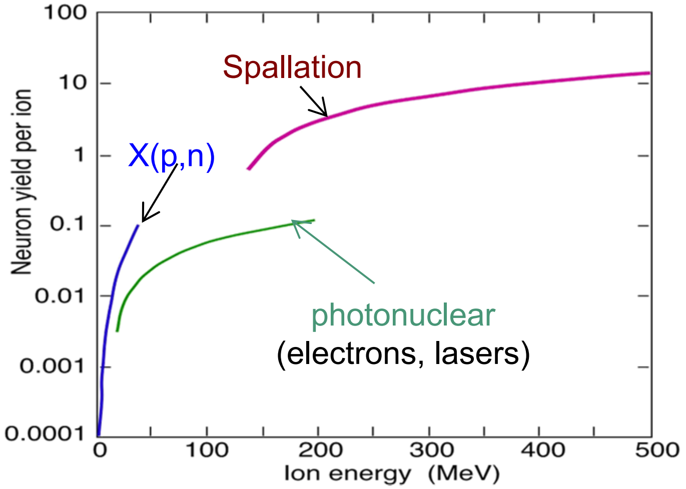


Fission



Watanabe 2003

Spallation



More Neutron Producing Reactions

Reaction types	Examples
(p,n)	^{3}H(p,n)^{3}He, ^{6}Li(p,n)^{6}Be, ^{7}Li(p,n)^{7}Be, ^{9}Be(p,n)^{9}B, ^{10}Be(p,n)^{10}B, ^{10}B(p,n)^{10}C, ^{11}B(p,n)^{11}C, ^{12}C(p,n)^{12}N, ^{13}C(p,n)^{13}N, ^{14}C(p,n)^{14}N, ^{15}N(p,n)^{15}O, ^{18}O(p,n)^{18}F, ^{36}Cl(p,n)^{36}Ar, ^{39}Ar(p,n)^{39}K, ^{59}Co(p,n)^{59}Ni
(d,n)	^{2}H(d,n)^{3}He, ^{3}H(d,n)^{4}He, ^{7}Li(d,n)^{8}Be, ^{9}Be(d,n)^{10}B, ^{11}B(d,n)^{12}C, ^{13}C(d,n)^{14}N, ^{1}4N(d,n)^{15}O, ^{15}N(d,n)^{16}O, ^{18}O(d,n)^{19}F, ^{20}Ne(d,n)^{21}Na, ^{24}Mg(d,n)^{25}Al, ^{28}Si(d,n)^{29}P, ^{32}S(d,n)^{33}Cl
(t,n)	^{1}H(t,n)^{3}He
(α,n)	^{3}H(α,n)^{6}Li, ^{7}Li(α,n)^{10}B, ^{11}B(α,n)^{14}N, ^{13}C(α,n)^{16}O, ^{22}Ne(α,n)^{25}Mg

Drosg *et al.* (2002)

Source Characteristics *(Bauer01, Clausen08, Mank et al.01, Zager et al. 05, Nakai et al.10, Elizondo-Decanini et al12)*

Reactions	Neutron Yield	Neutron Production*	Heat Release (MeV/n)	Remarks
Spallation	17-27n/p	10^{14} (n/s/cm^2)	30-55	Expensive, complex, adamant usage
Fission	1 n/fission	10^{13}-10^{15} (n/s/cm^2)	180	Expensive, complex, adamant usage
Giant laser inertial fusion	1 n/D-T pair	> 10^{16} (n/s/cm^2)	Re-stockable D-T pellets	Unattainable?
^{9}Be(D,n)^{10}Be ^{9}Be(p,xn)	1 n/D 5x10^{-3} n/p	10^{13}-10^{15} (n/s/cm^2)	1000 2000	Moderate cost, flexible operation, multipurpose
Photonuclear e-bremsstrahlung	5x10^{-2} n/e	10^{13} (n/s/mA)	2000	Moderate cost, flexible operation, multipurpose
Neutron Generators (D,D) (D,T)	10^{7}-10^{8} n/μC	10^{8} -10^{10} (n/s)	3500-10000	Transportable, affordable for tailored commercial applications, need higher flux
Table-top-laser photonuclear	10^{6}-10^{8} n/J	10^{8} -10^{10} (per shot)	Ultra-short pulsed lasers	Many debris, neutronics not yet matured
Neutristors solid-state, (D,D) chips	?	?	?	~$2000, tiny, implantable medically, to be developed

*need quantification of neutron spectral distribution and time structure

Neutron Sources

Big

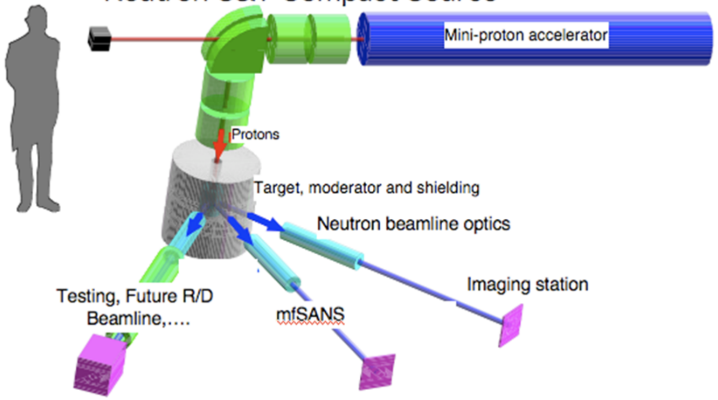

FRM-II High Flux Reactor


Spallation Neutron Source

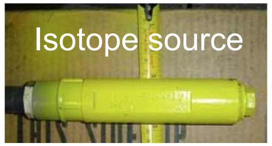

PSI Cyclotron-driven source

Medium

Compact Accelerator-Driven Sources


Neutron S&T Compact Source

Small


Isotope source


Neutron generator


Neutron Interrogation Device

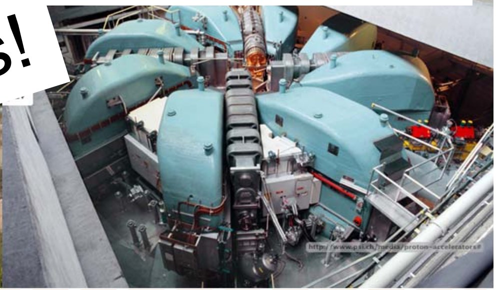

PGNAA

Neutron Sources

Big

FRM-II High Flux Reactor

Spallation Neutron Source



PSI Cyclotron-driven source

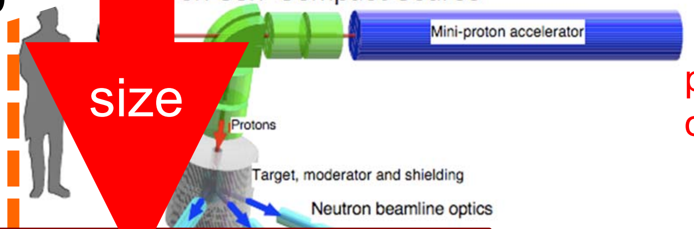
Everything is relative, so is compactness!

Medium

Compact Acc

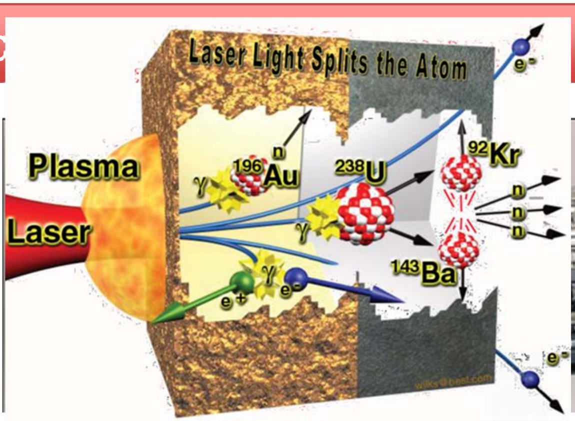
100kW

…ron S&T Compact Source



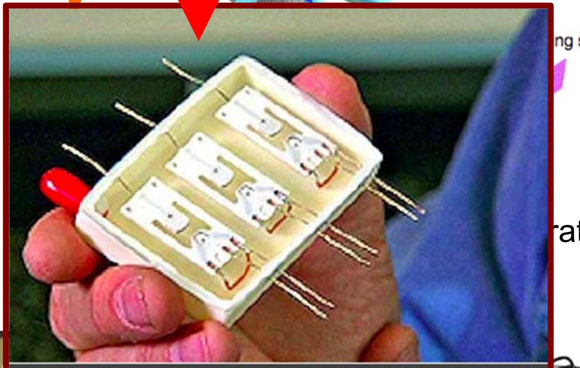
Small Reactors

p, d
or e⁻



size

flux



Sandia neutrister neutron generators mounted in a test box under vacuum

ng station

ator

Neutron Interrogation Device

PGNAA

Small

Isotope s

Neutron Sources: Past, Present, & Future

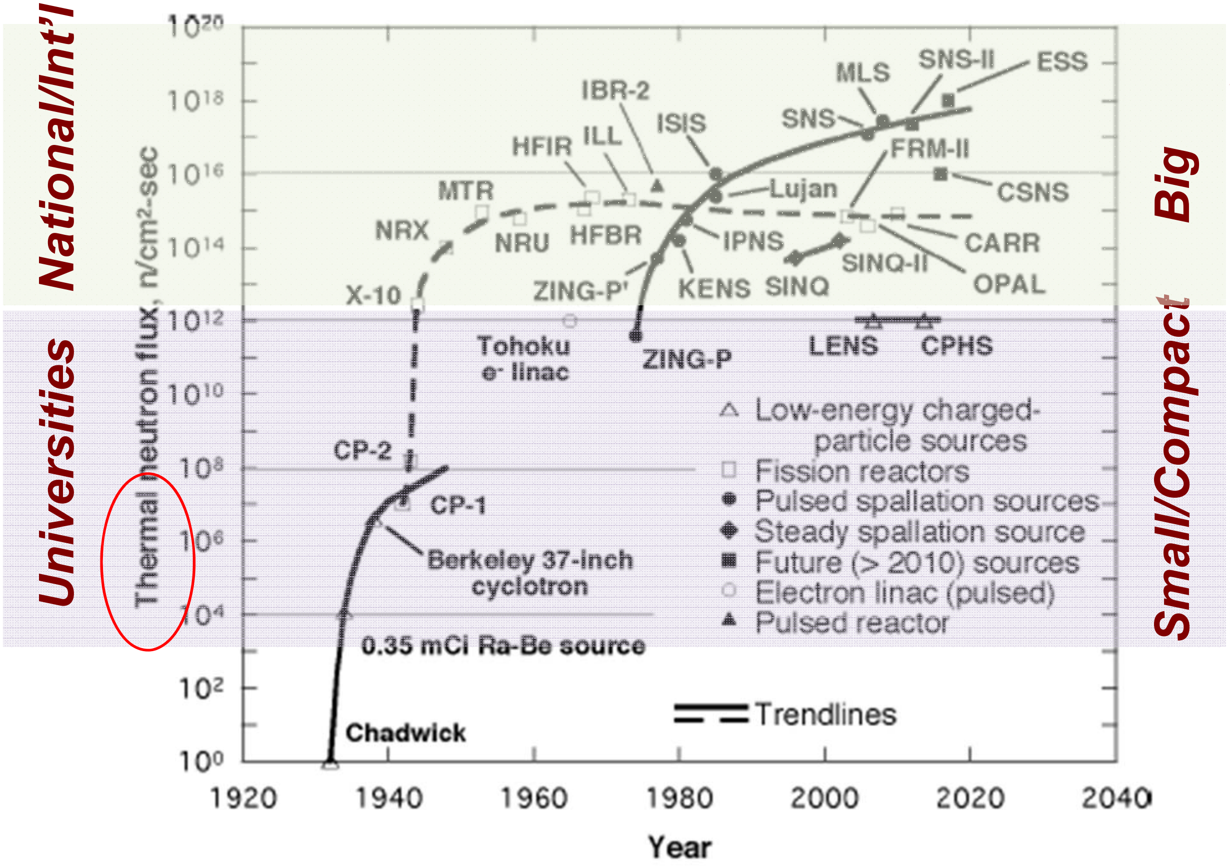
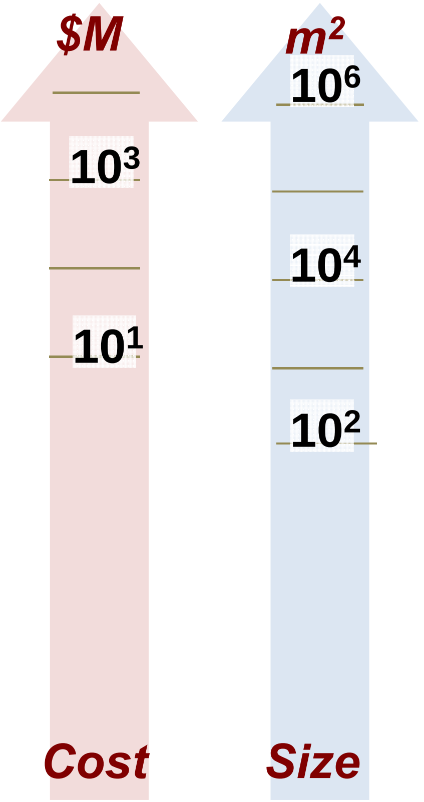


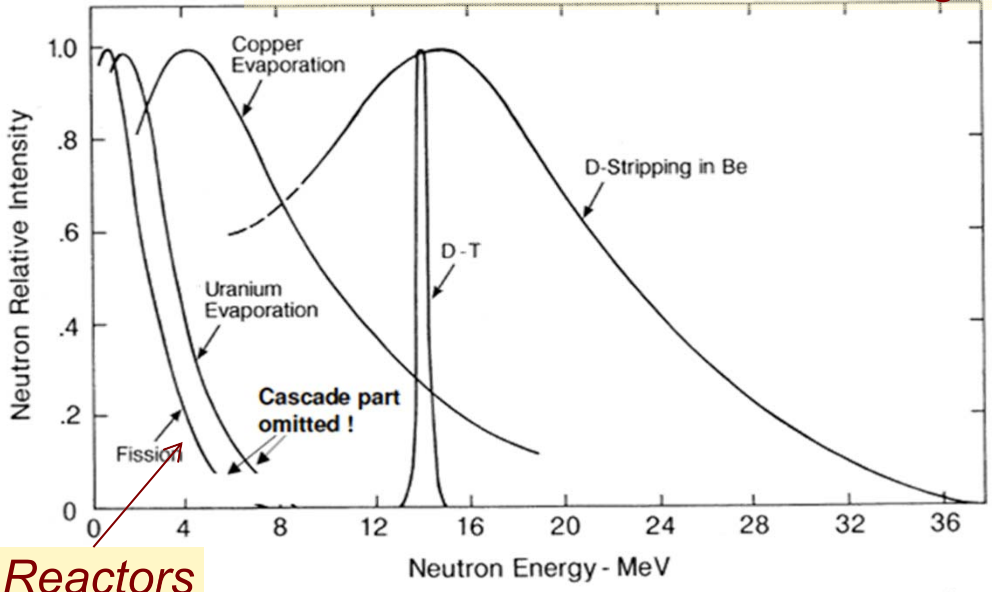
Figure 1. History of development of neutron sources in terms of the effective thermal neutron flux. Carpenter & Lander 2010



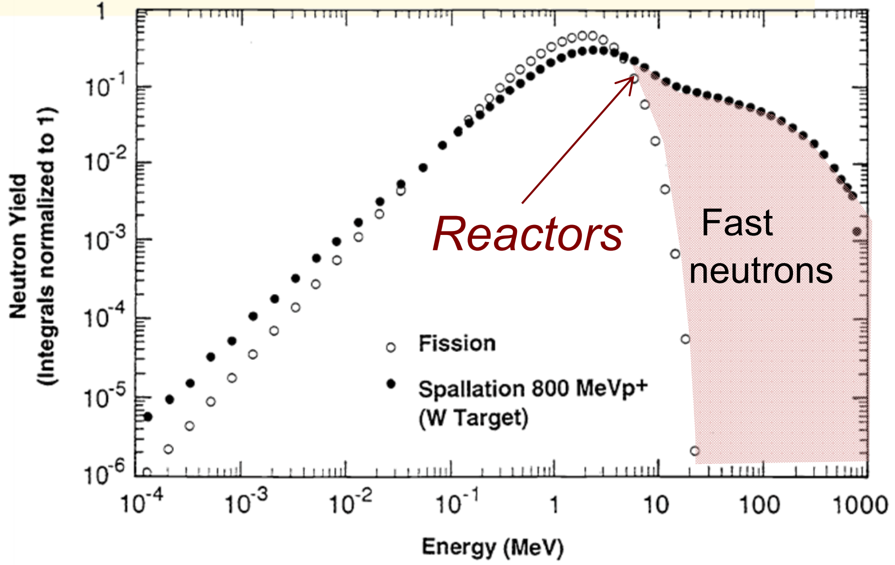
This is not the whole story!

Neutron Energy Spectrum & Time Structure

Accelerator-driven sources generates 10-100 MeV fast neutrons



Reactors



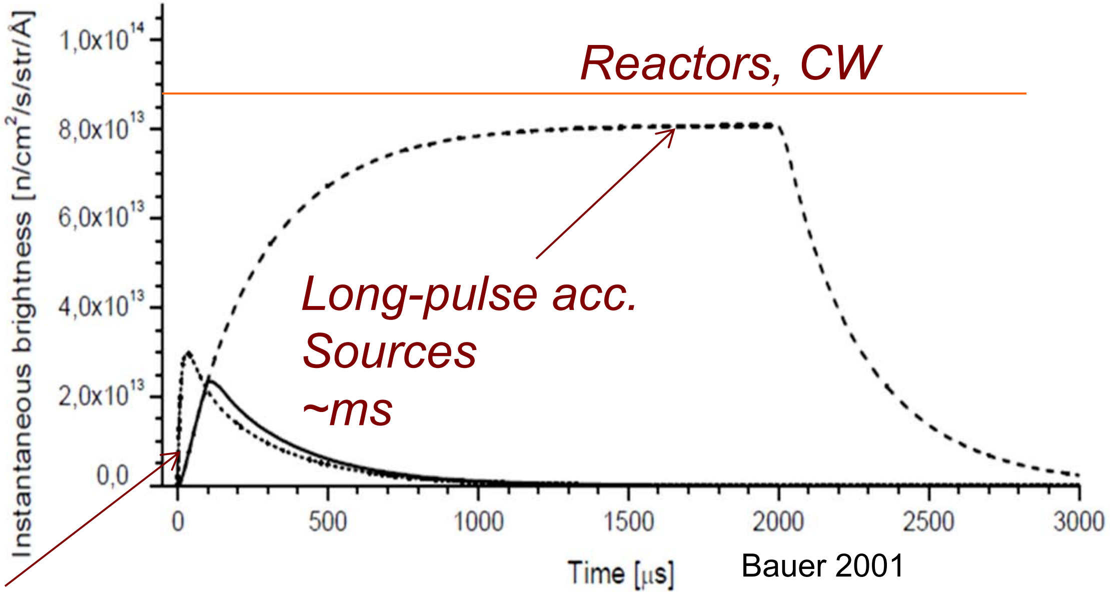
Reactors

Fast neutrons

Accelerator-driven sources generate neutrons with

- *a wide energy spectrum, providing cold, thermal, epithermal, and fast neutrons*
- *A distinct time structure from μs to ms*

Therefore, accelerator-based sources lend more applications(?).



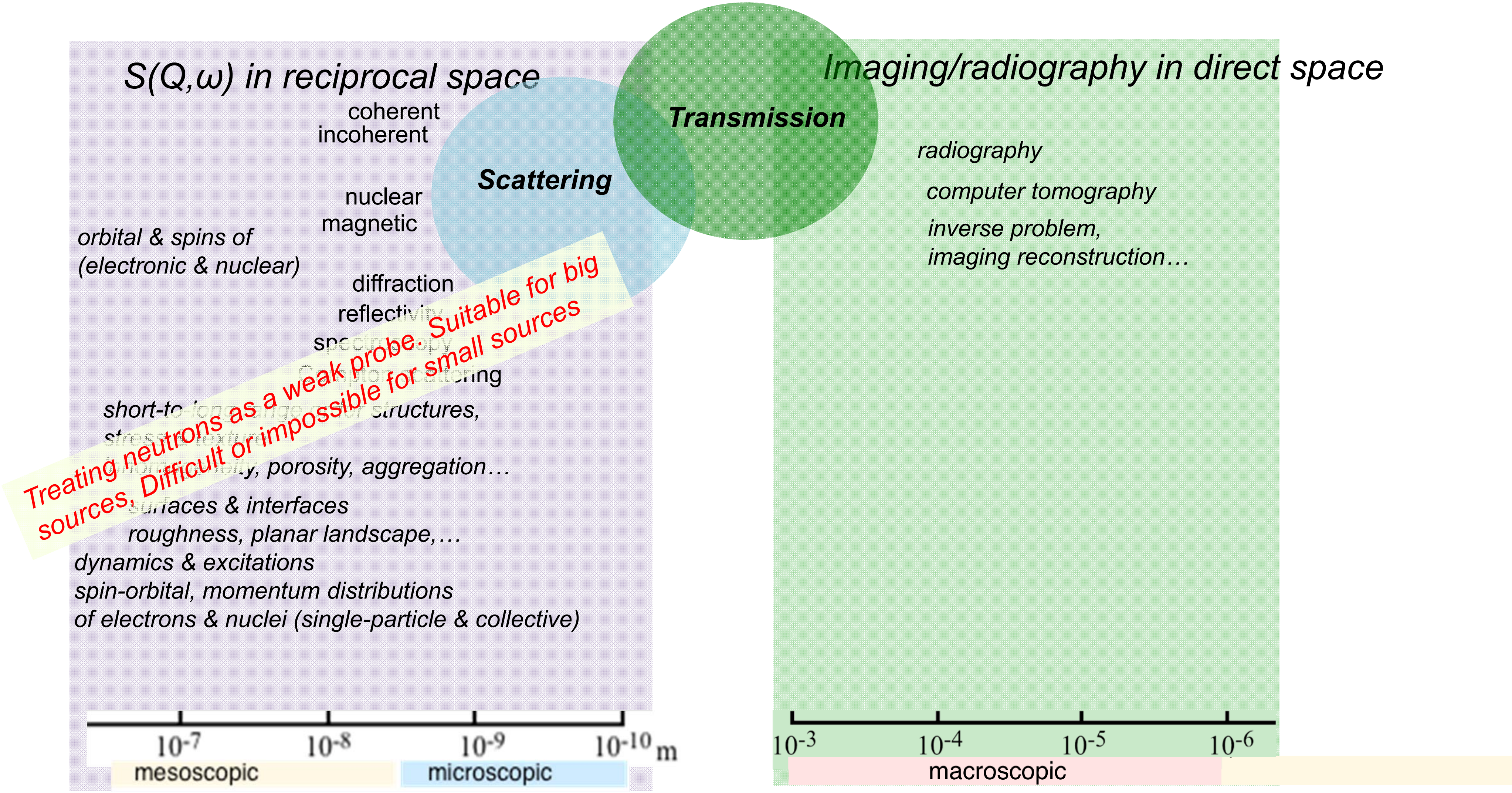
Reactors, CW

Long-pulse acc. Sources ~ms

Bauer 2001

Short-pulse acc. sources

Applications of CANS: A Prelude to Lecture III



S(Q,ω) in reciprocal space

coherent
incoherent

nuclear
magnetic

orbital & spins of
(electronic & nuclear)

diffraction
reflectivity
spectroscopy
Compton scattering

short-to-long range order structures,
stress & texture
inhomogeneity, porosity, aggregation…
surfaces & interfaces
roughness, planar landscape,…
dynamics & excitations
spin-orbital, momentum distributions
of electrons & nuclei (single-particle & collective)

Scattering

Transmission

Imaging/radiography in direct space

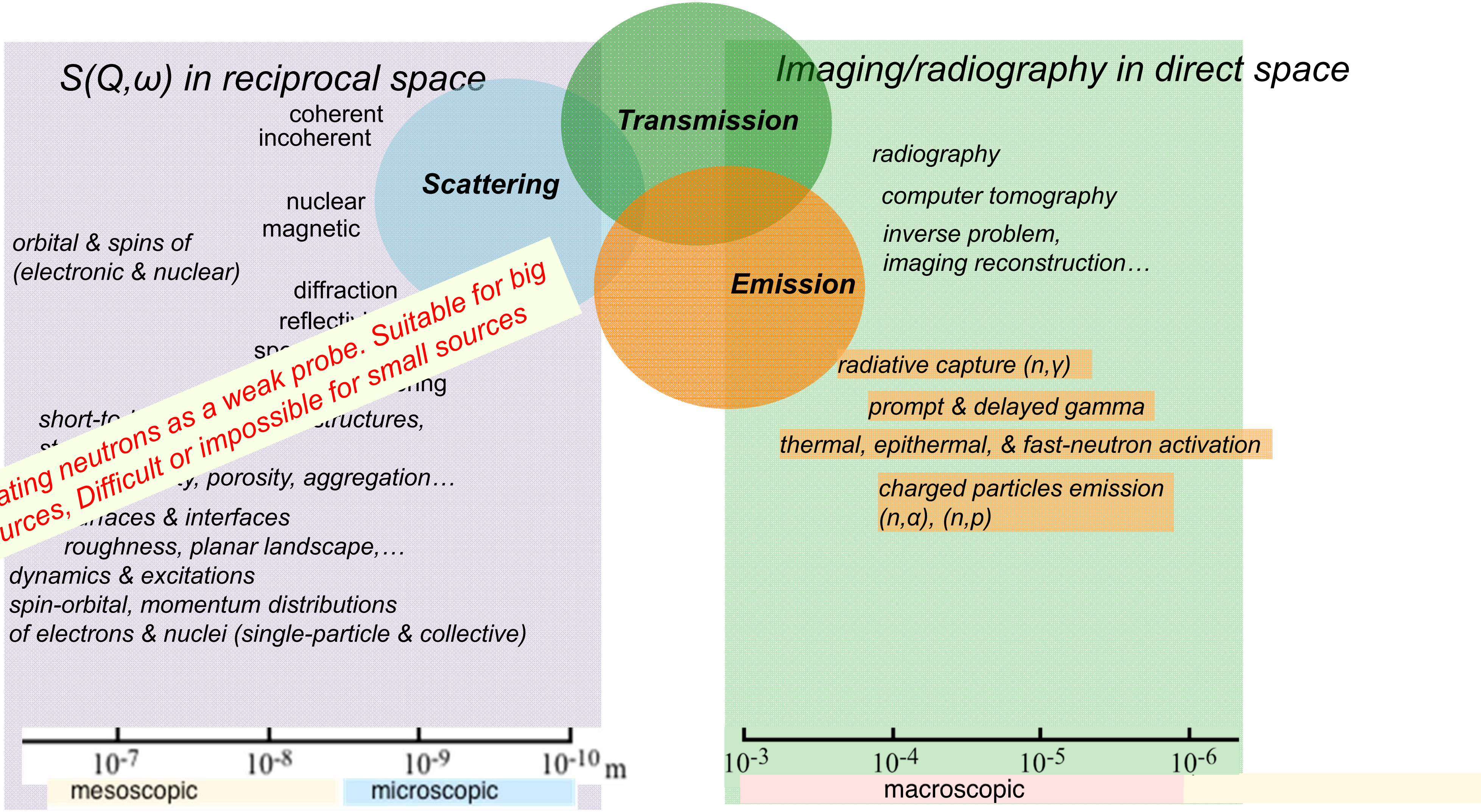
radiography

computer tomography

inverse problem,
imaging reconstruction…

Treating neutrons as a weak probe. Suitable for big sources, Difficult or impossible for small sources

Applications of CANS: A Prelude to Lecture III



S(Q,ω) in reciprocal space

coherent
incoherent

nuclear
magnetic

orbital & spins of
(electronic & nuclear)

diffraction
reflecti
sp
ring

short-to
tructures,
y, porosity, aggregation…
aces & interfaces
roughness, planar landscape,…
dynamics & excitations
spin-orbital, momentum distributions
of electrons & nuclei (single-particle & collective)

10^{-7} 10^{-8} 10^{-9} 10^{-10} m

mesoscopic
microscopic

Scattering

Transmission

Emission

Imaging/radiography in direct space

radiography

computer tomography

inverse problem,
imaging reconstruction…

radiative capture (n,γ)

prompt & delayed gamma

thermal, epithermal, & fast-neutron activation

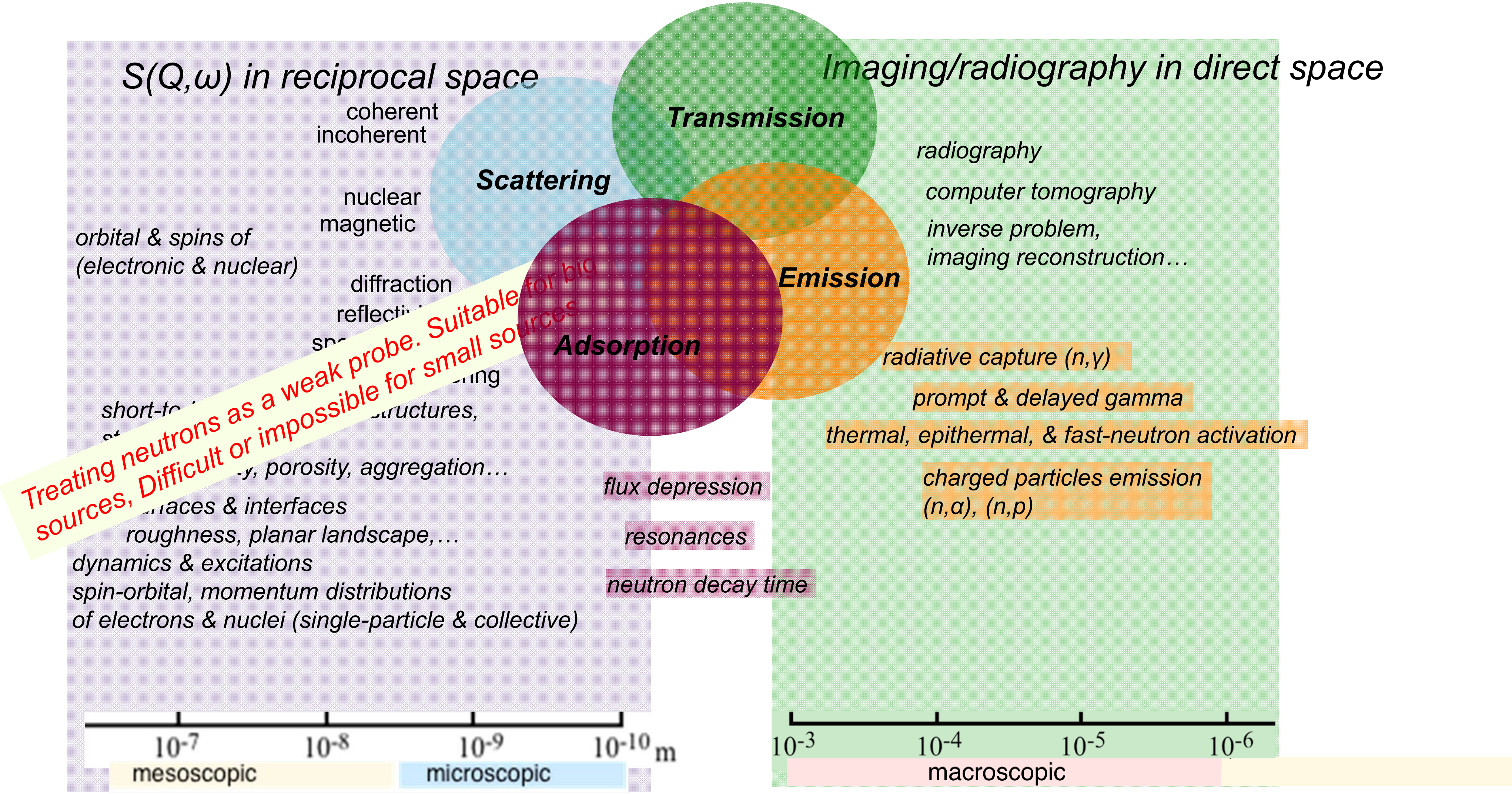
charged particles emission
(n,α), (n,p)

10^{-3} 10^{-4} 10^{-5} 10^{-6}

macroscopic

Treating neutrons as a weak probe. Suitable for big sources, Difficult or impossible for small sources

Applications of CANS: A Prelude to Lecture III



S(Q,ω) in reciprocal space

coherent
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short-to
structures,
st
y, porosity, aggregation…
rfaces & interfaces
roughness, planar landscape,…
dynamics & excitations
spin-orbital, momentum distributions
of electrons & nuclei (single-particle & collective)

Treating neutrons as a weak probe. Suitable for big sources, Difficult or impossible for small sources

Scattering

Transmission

Emission

Adsorption

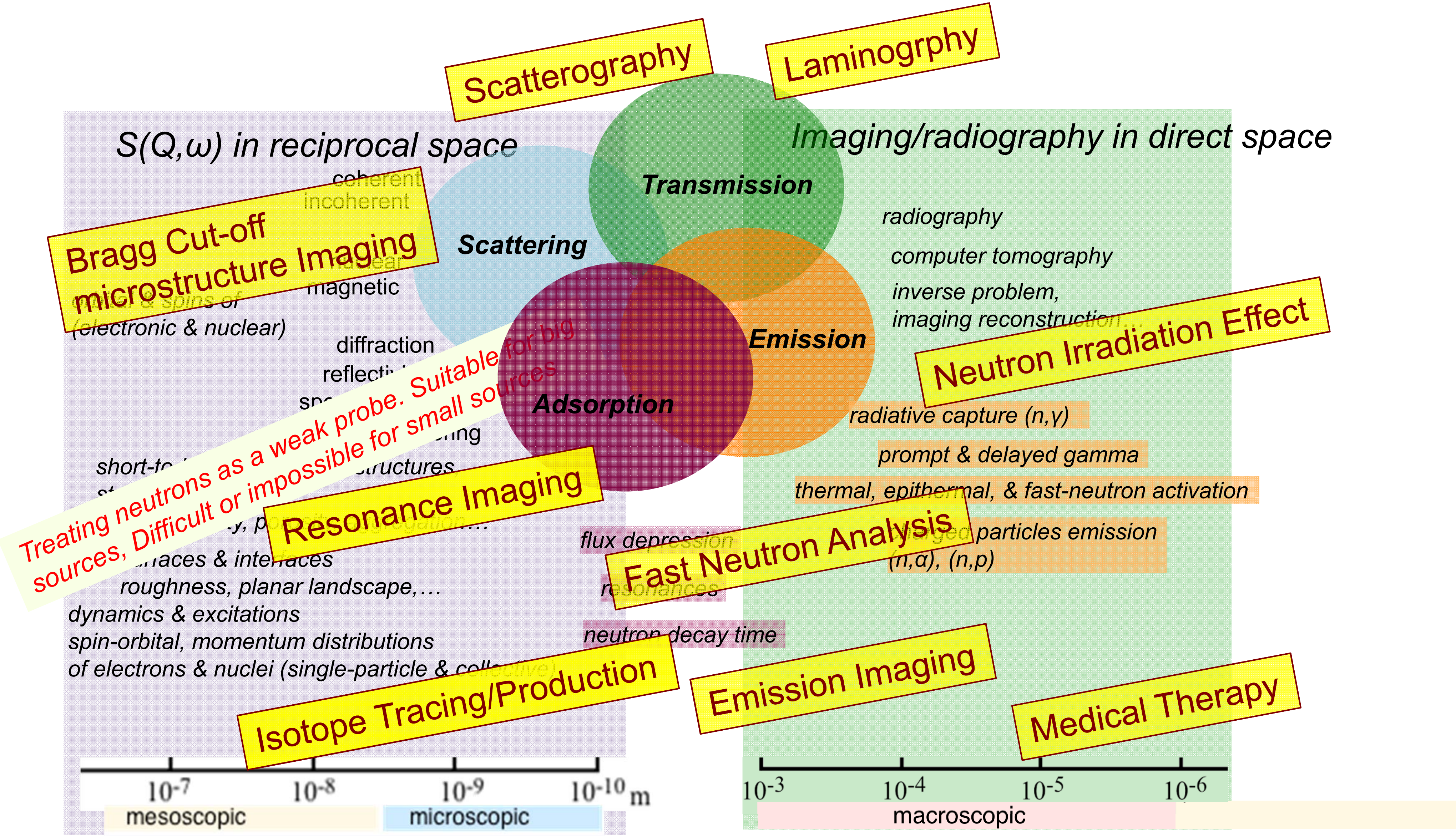
flux depression
resonances
neutron decay time

Imaging/radiography in direct space

radiography
computer tomography
inverse problem,
imaging reconstruction…

radiative capture (n,γ)
prompt & delayed gamma
thermal, epithermal, & fast-neutron activation
charged particles emission
(n,α), (n,p)

Applications of CANS: A Prelude to Lecture III



Scatterography

Laminogrphy

S(Q,ω) in reciprocal space

Imaging/radiography in direct space

Transmission

Scattering

Emission

Adsorption

coherent
incoherent
nuclear
magnetic
orbital & spins of
(electronic & nuclear)

diffraction
reflecti...
sp...
...ring

short-to-...
...structures,
st...
...y, p... segregation…
...rfaces & interfaces
roughness, planar landscape,…
dynamics & excitations
spin-orbital, momentum distributions
of electrons & nuclei (single-particle & collective)

Bragg Cut-off microstructure Imaging

Treating neutrons as a weak probe. Suitable for big sources, Difficult or impossible for small sources

Resonance Imaging

Isotope Tracing/Production

radiography
computer tomography
inverse problem,
imaging reconstruction…

Neutron Irradiation Effect

radiative capture (n,γ)
prompt & delayed gamma
thermal, epithermal, & fast-neutron activation
charged particles emission
(n,α), (n,p)

flux depression
resonances
neutron decay time

Fast Neutron Analysis

Emission Imaging

Medical Therapy

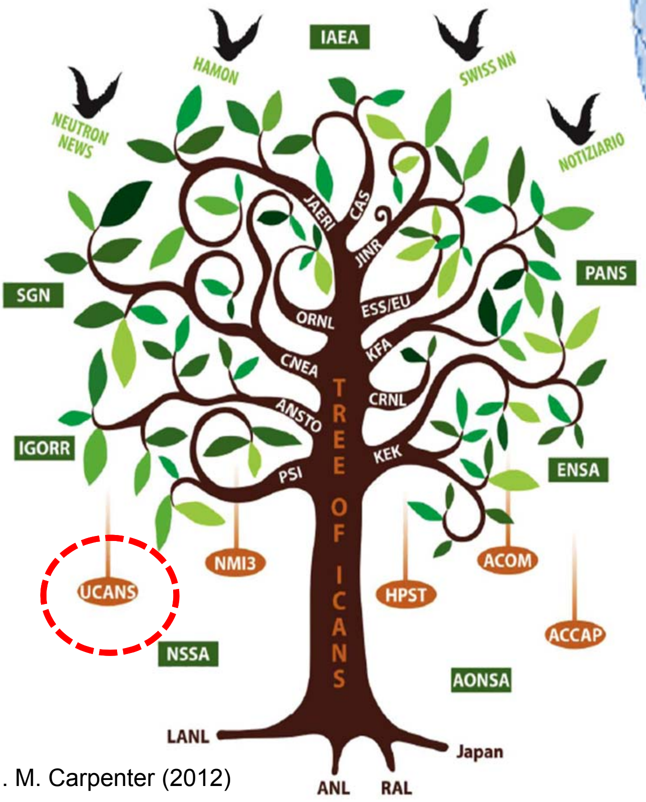
10-7, 10-8, 10-9, 10-10 m
mesoscopic, microscopic

10-3, 10-4, 10-5, 10-6
macroscopic

… and More …

Union for Compact Accelerator-driven Neutron Sources (UCANS) Established in 2008

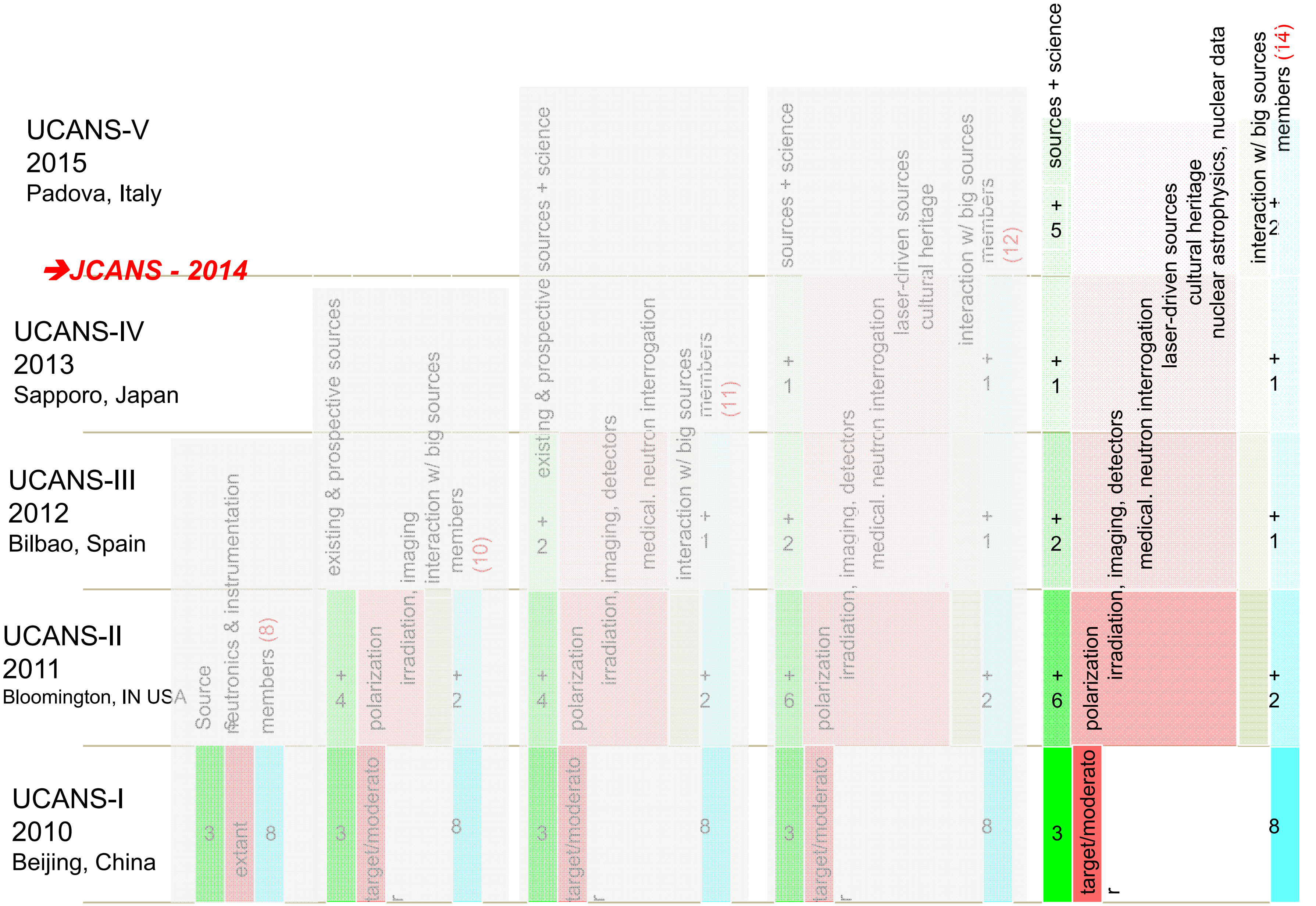
- ✧ Established in 2008
- ✧ 14 members in Americas, Asia and Europe, encompassing
    - ✧ Academia
    - ✧ Government labs
    - ✧ Industry



J. M. Carpenter (2012)

Neutron News, **25**(2), 12 (2014);
ibid **22**(1), 7 (2011)

Collaborative & Complementary: Capability vs Capacity



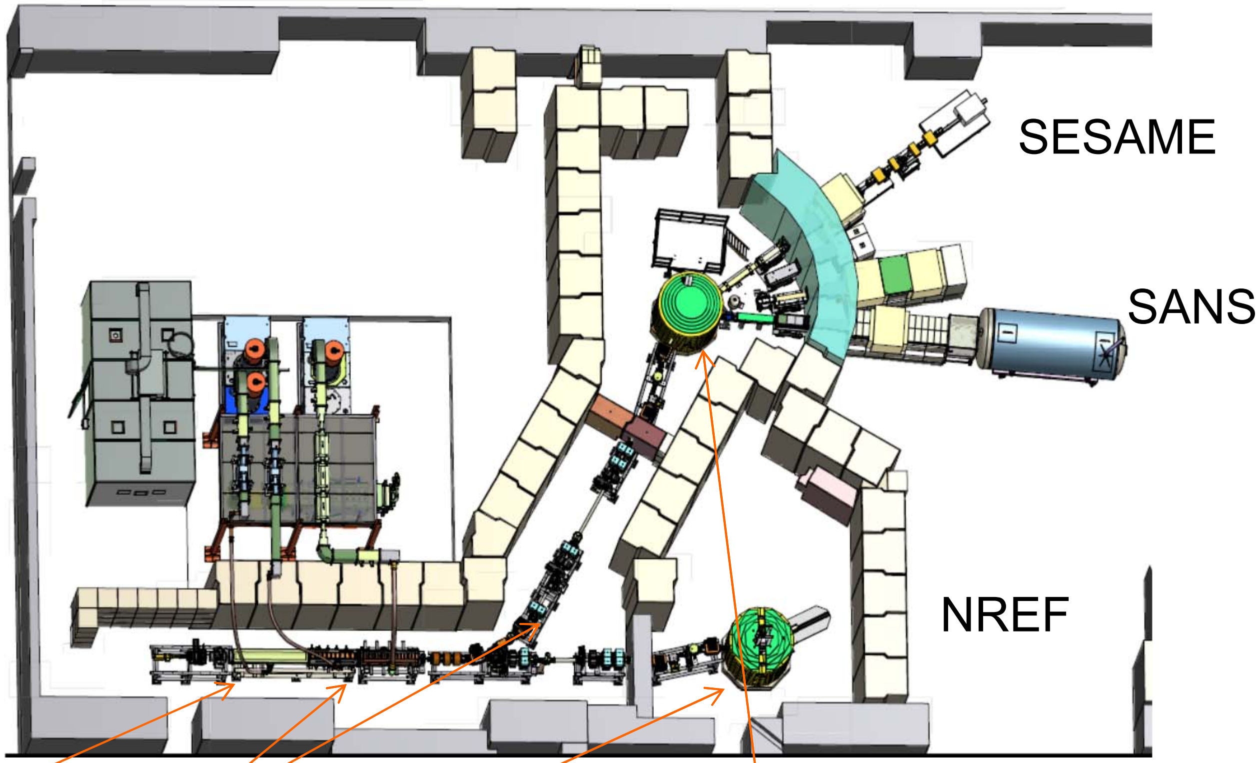
This slide needs to be checked and brought up to date

Compact Accelerator-driven Neutron Sources (CANS) Currently in Operation or under Development

There is an active CANS community

The Low-Energy Neutron Source (LENS)

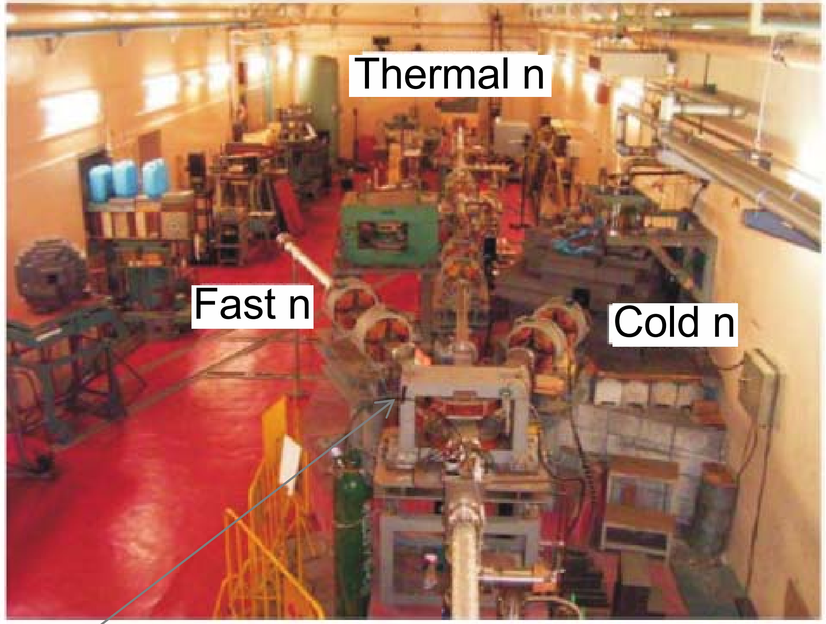
Indian University, Bloomington, USA



Proton RFQ + 2 linacs	Target station 1	Target station 2	Major activities
13 MeV, 25 mA (peak) <~4kW Long pulse, width 0.6 ms, 20 Hz	Be(p, n) PE/PE w Cd/none ~2x10^{10} n/cm^2/s	Be(p, n) Methane 4K ~1x10^{13} n/s	TS1: radiation effects, imaging TS2: SANS, spin polarized reflectometry Detector/optics/moderator R&D Education

The Hokkaido University Neutron Source (HUNS)

Sapporo, Hokkaido, Japan



Electron linac

35 MeV, 30 μA (50 ps)
1kW
Short pulse, width 10ns-3μs
50 or 100 Hz

Target station

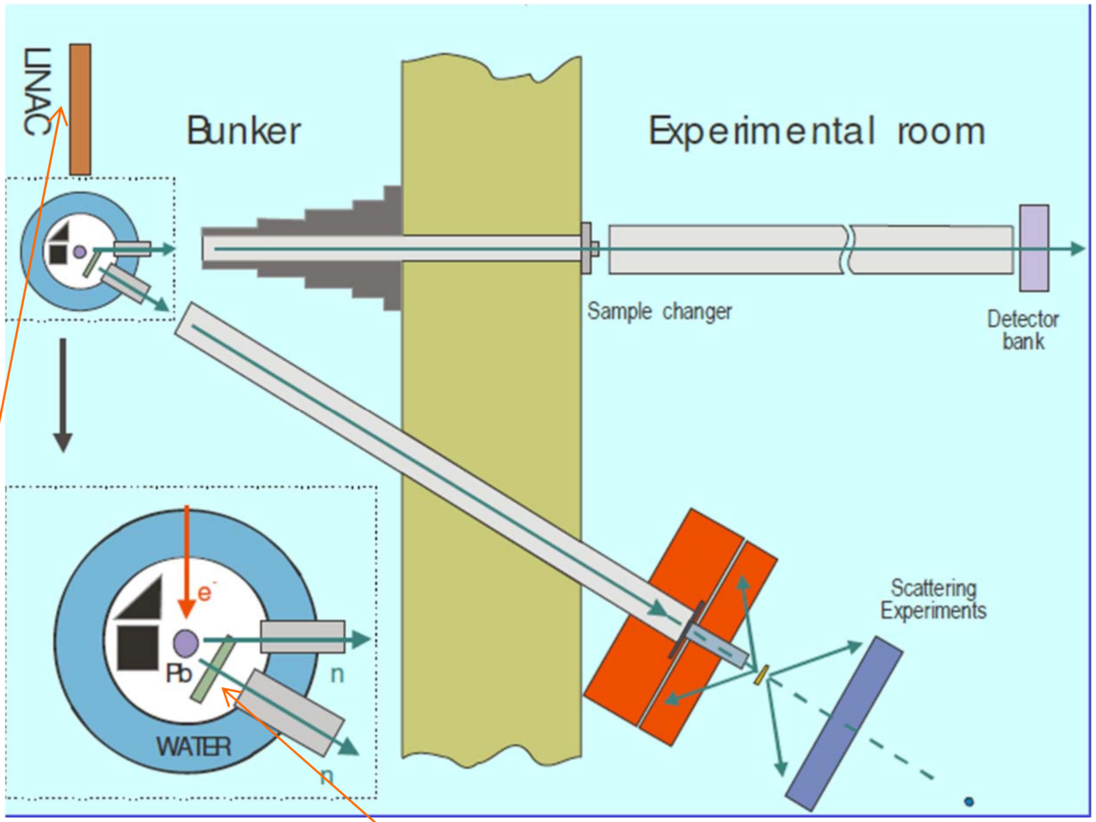
(e, X), (X,n)
water/coupled methane
1.6x10^{12} n/s

Major activities

Radiation effects, imaging
Detector/device/moderator R&D
Education
Small-to-wide angle diffraction

The Bariloche Electron-linac-based Neutron Source

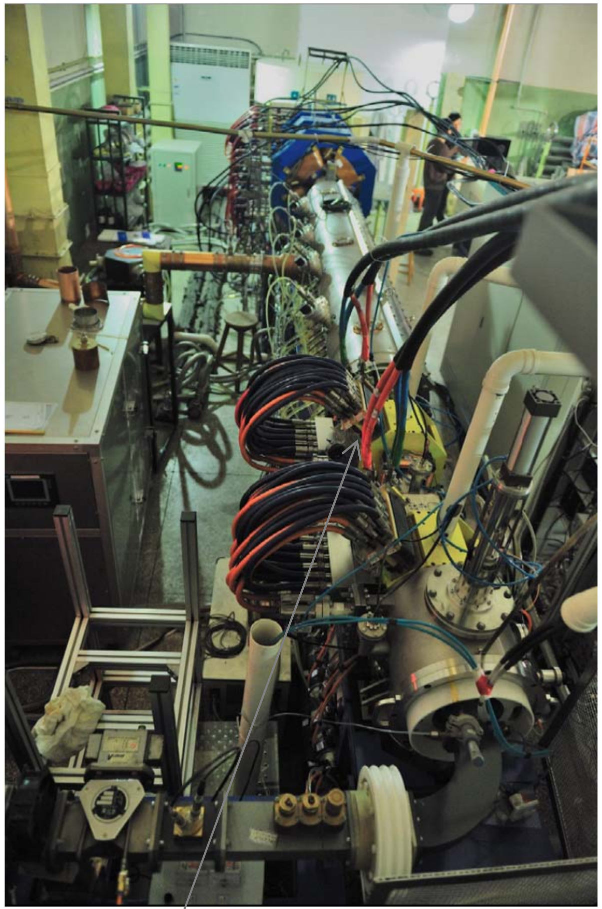
Bariloche, Argentina



Electron linac	Target station	Major activities
25 MeV, 25-30 μA Short pulse, width 1.4μs up to 100 Hz	(e, X), (X,n) PE/ mesitylene@77K ~6x10^{11} n/s	Total cross section measurements Diffraction, DINS Device/moderator R&D Education

Peking University Neutron Imaging Facility (PKUNIFTY)

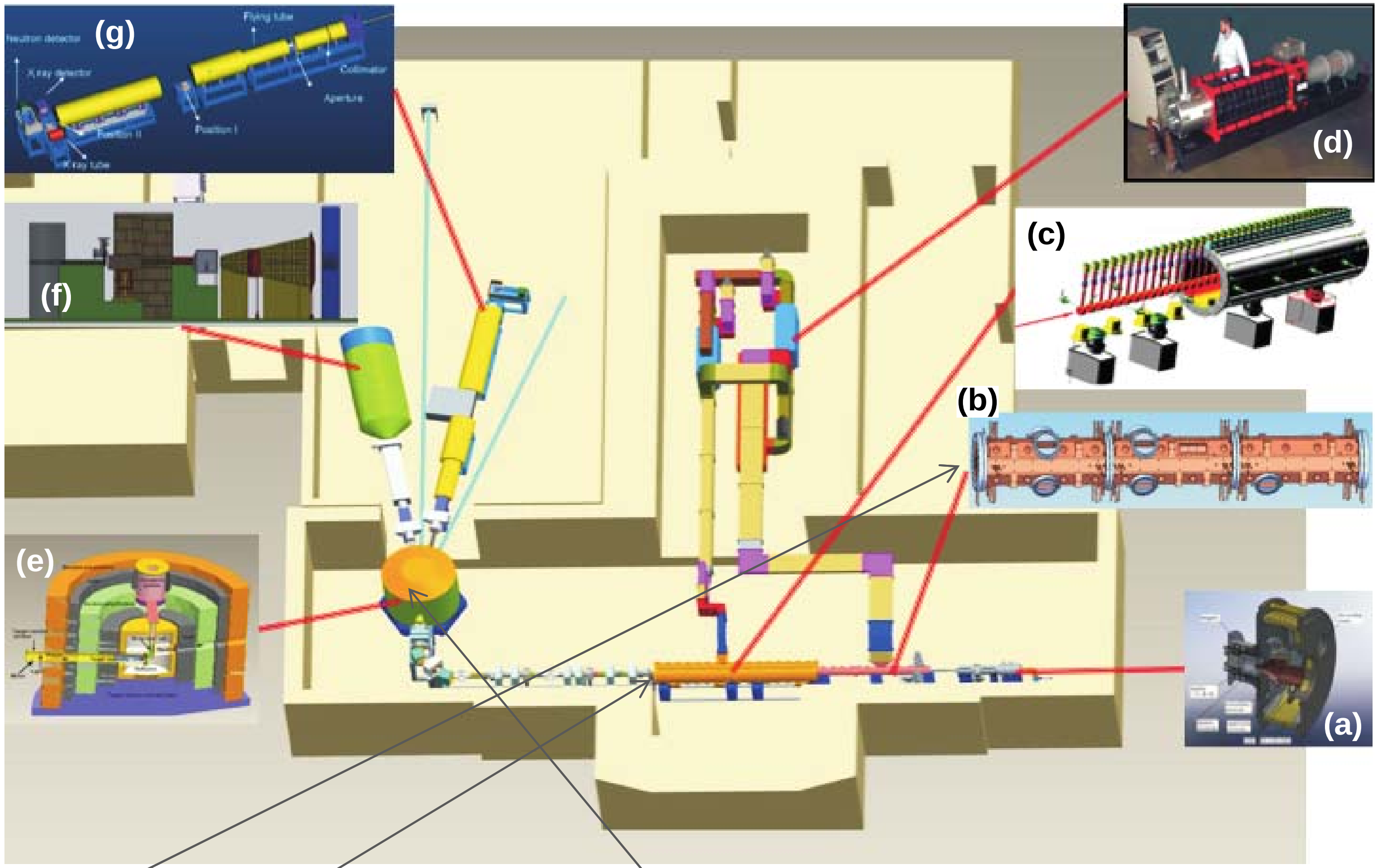
Beijing, China



RFQ linac	Target station	Major activities
Deuterons, 2 MeV, 40mA (peak) Long pulse, width 0.015-0.8 ms for <10-40 Hz; Normal operation 20Hz, width 0.6ms	Be(d,n) PE + H_2O 3×10^{12} n/s	Imaging, cross section measurements Education

The Compact Pulsed Hadron Source (CPHS)

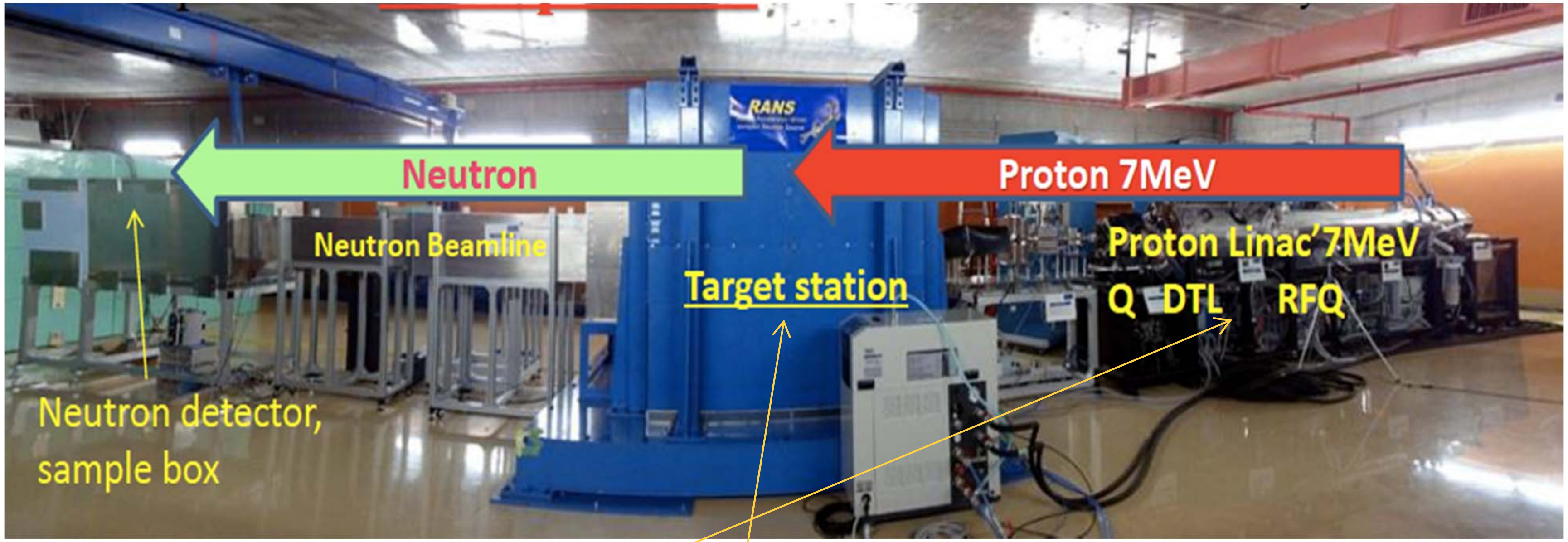
Tsinghua University, Beijing, China



Proton RFQ + 1 linac	Target station	Major activities
3MeV(initial) 13 MeV(final), 16KW 50 mA (peak), 1.25 mA (average) Long pulse, width 0.5 ms, 50 Hz	Be(p, n) PE(initial), Solid methane (final) ~5x10^{13} n/s	Imaging, SANS Detector/device R&D Education

RIKEN Accelerator-driven Neutron Source (RANS)

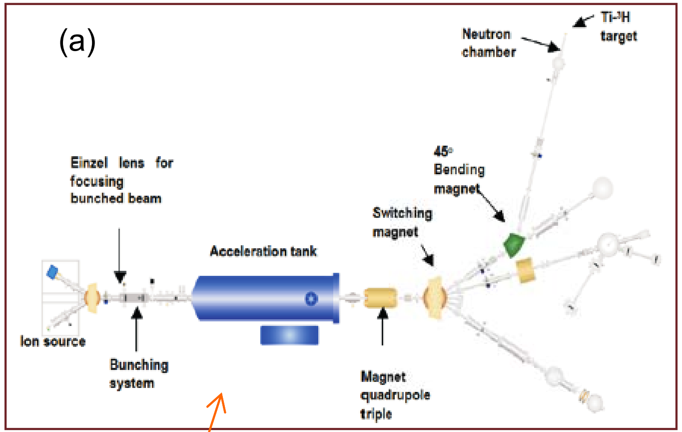
Tokyo, Japan

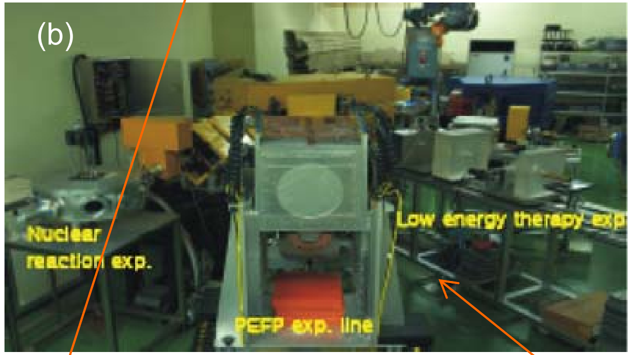


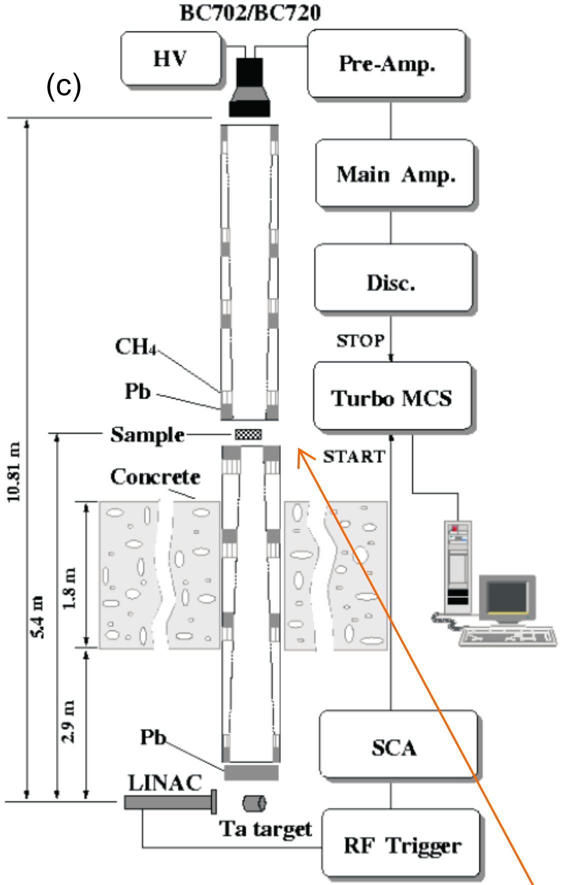
Proton RFQ + 1 linac	Target station	Major activities
7 MeV, 16KW 10 mA (peak), 100 μA (average) Long pulse, width 0.5 ms, 20 Hz	Be(p, n) PE(initial), cold mesitylene (final) ~1x10^{12} n/s	Imaging, industrial applications Fast neutron interrogation

The KIGAM, MC-50, & PAL-PNF Facilities

S. Korea



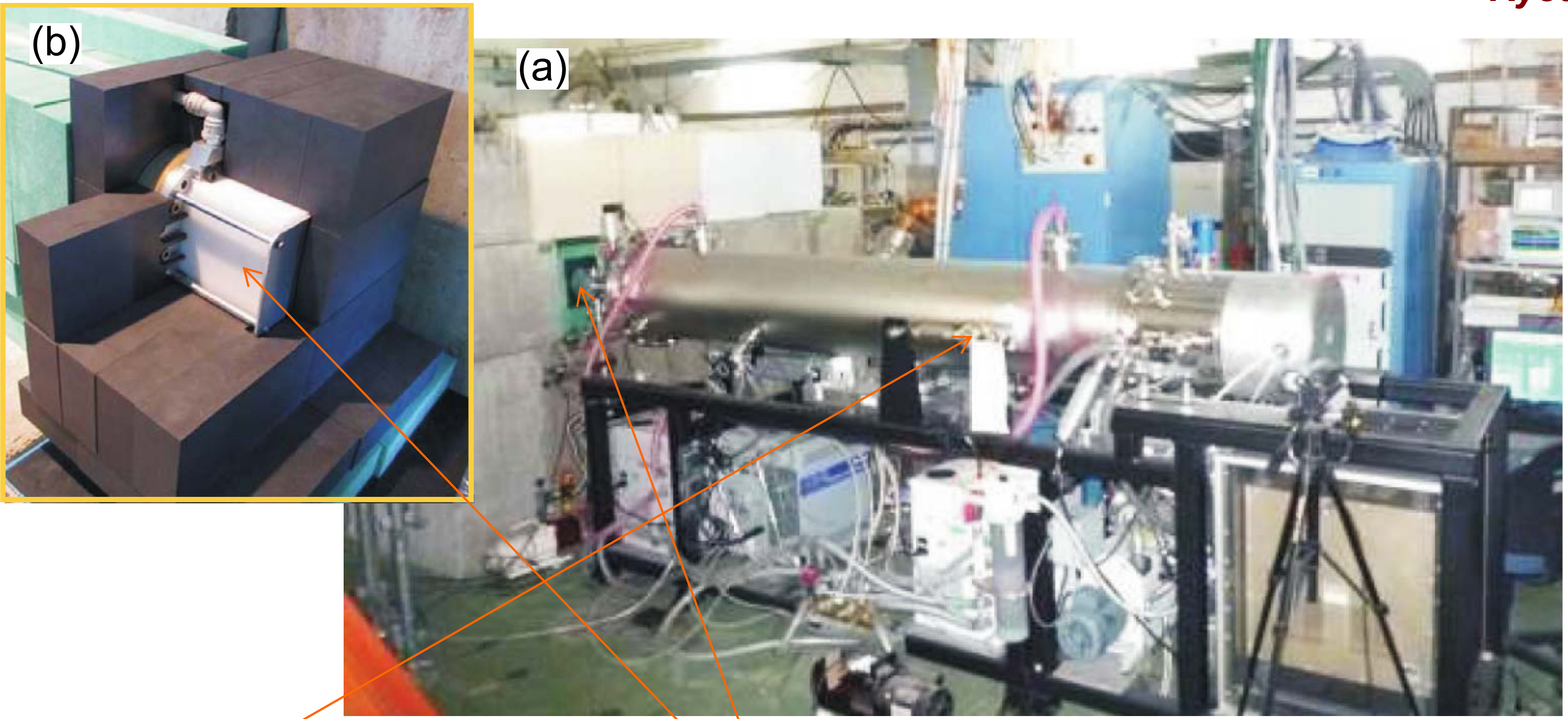




KIGAM	MC-50	PAL-PNF
1.7 MV tandem accelerator Pulsed: 4 MHz, width 1-2 ns ^{3}H(p,n)^{3}He: selective mono-energies 0.144-2.5 MeV, 10^2-10^3 n/cm^2/s Fast neutrons capture and elastic cross section measurements, education	MC-50 cyclotron (Scantronics) Protons: 20-51 MeV/60μA Deuteron: 10-25 MeV/30μA Neutrons: from Be(p, n) Fast neutron irradiation, therapy, cross section measurements	80-MeV e-linac, 30-60 mA (peak) Pulsed: width 1-2 μs, 30 Hz Water-cooled Ta Target ~2x10^{12} n/s (calc.) Cross section measurements Education

Kyoto University Accelerator-driven Neutron Source (KUANS)

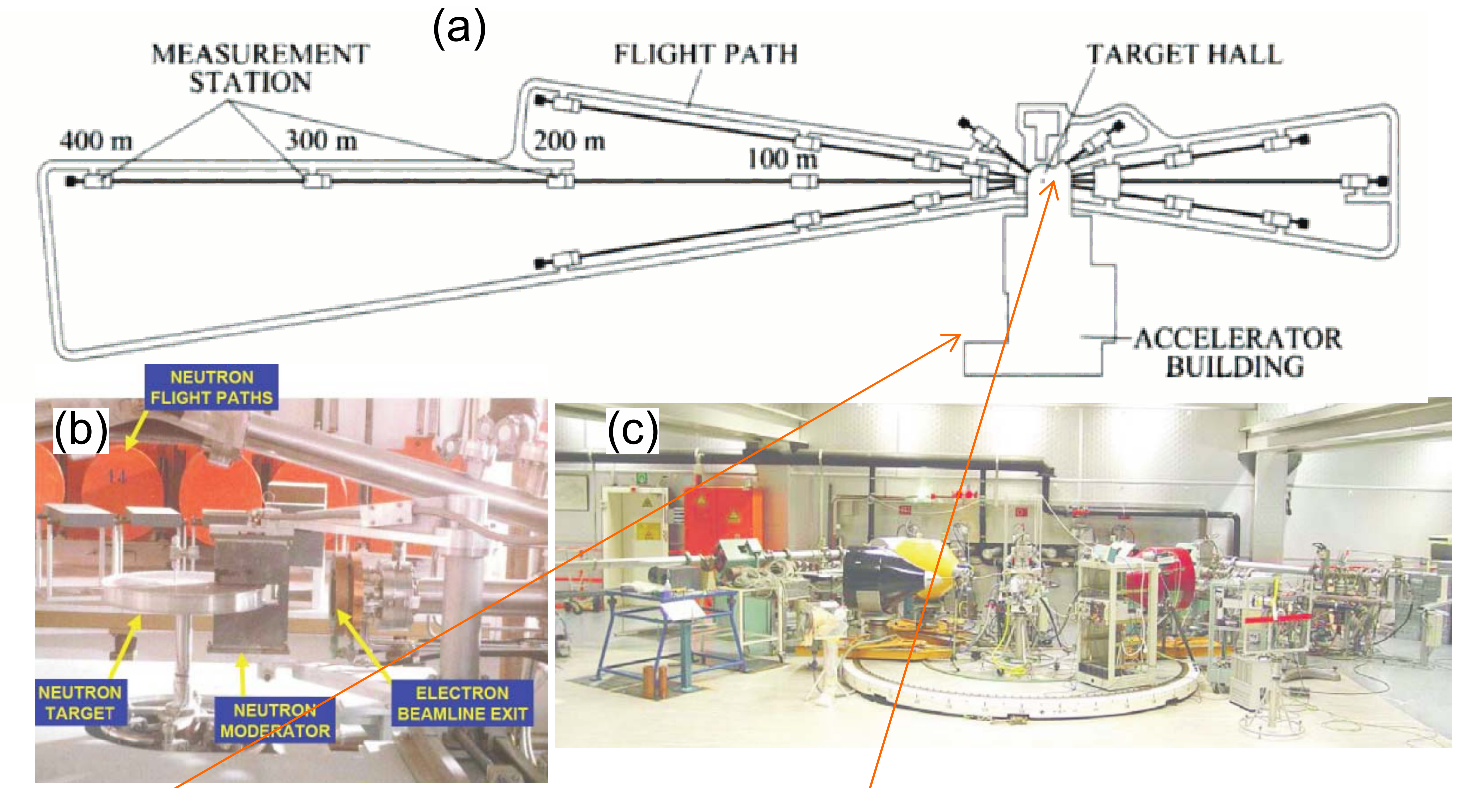
Kyoto, Japan



Proton RFQ (AccSys Tech. Inc.)	Target station	Major activities
3.5 MeV, 16KW 10 mA (peak), 100 µA (average) Long pulse, width 0.03-0.2 ms, 20-200 Hz	Be(p, n) PE, ambient ~1x10^{11} n/s (calc.)	Imaging, detector development, education

The Geel Electron LINear Accelerator Facility (GELINA)

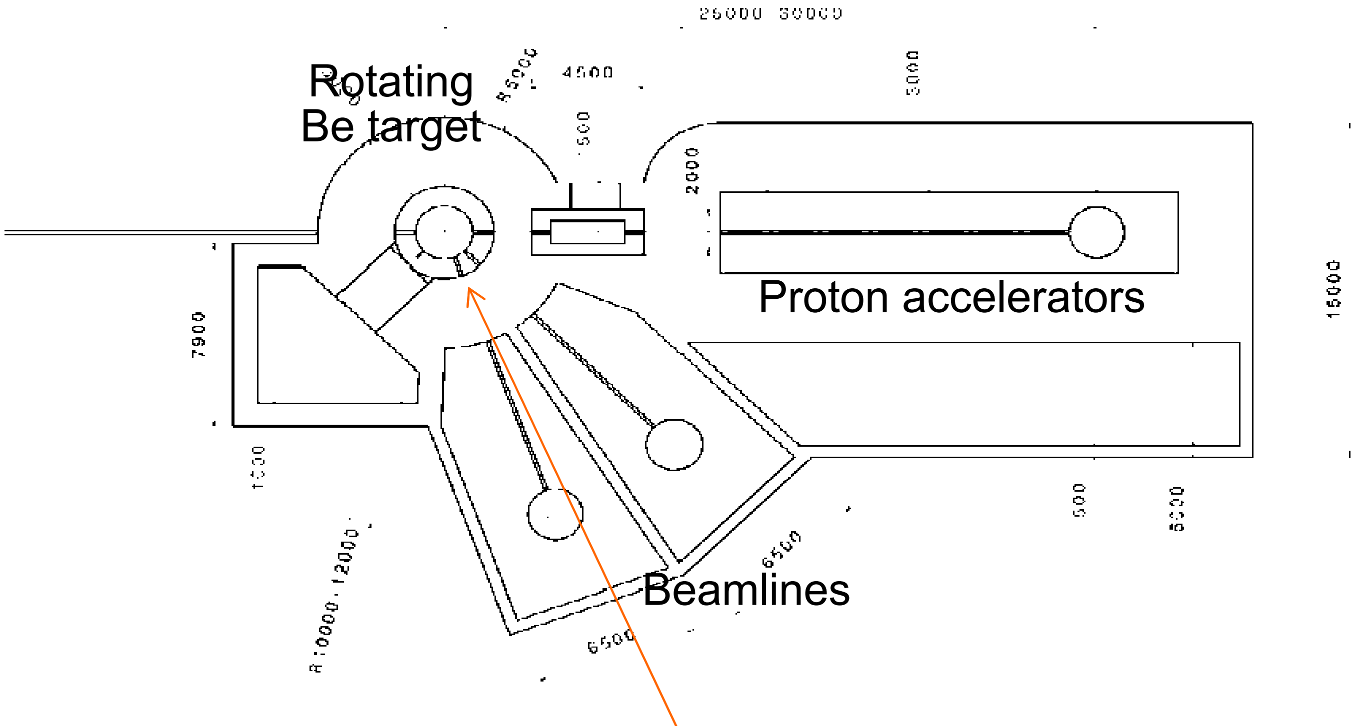
Belgium



7-MV de Graaff accelerator	Target Station	Major activities
Li(p,n), T(p,n), D(d,n), & T(d,n) 30 mA(max), 0.1-10 &13-21 MeV 3 x 10^8 n/s @ 2MeV, 30μA Short pulse, width < 1ns, rep. time 330ns	140 MeV, rotating U target, 4.7–75 μA water moderator Short pulse, width 1ns, 50-800 Hz $1.6\times10^{12} - 2.5 \times 10^{13}$ n/s	Total & partial cross section measurements Inelastic scattering, transmission, capture Nuclear data

The ESS-Bilbao Project

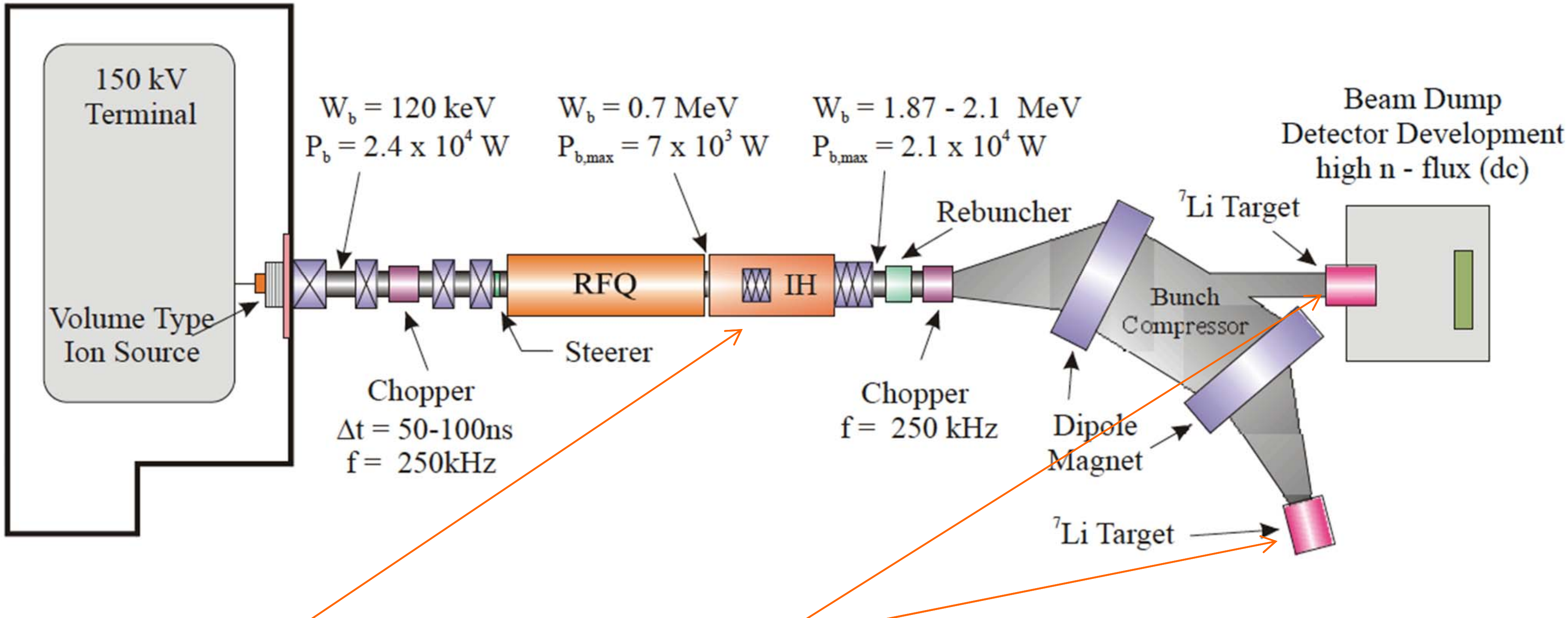
Bilbao, Spain



Proton linac	Target station	Major activities
50 MeV, 16KW 2.25 mA (average), 20 Hz Long pulse, width 1.5 ms	Be(p, n) Solid methane with water premoderator ~1x10^{15} n/s (calc.)	SANS, moderator and neutron-scattering component testing

The Frankfurt Neutron Source (FRANZ)

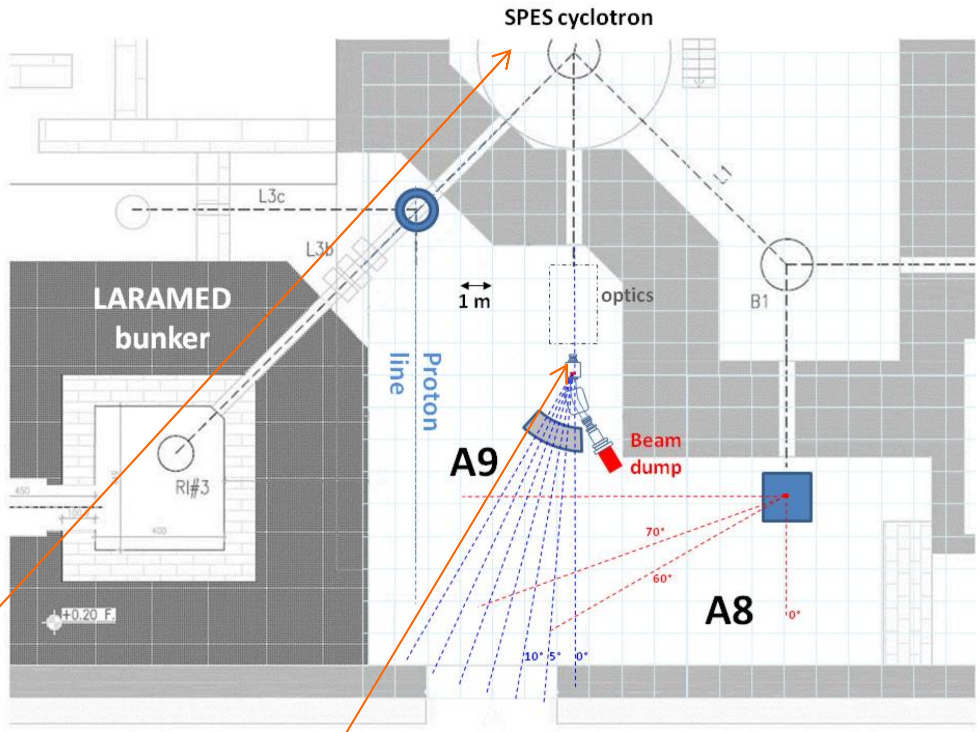
Stern-Gerlach-Zentrum, Germany



Proton linac	Target station	Major activities
1.87-2.1 MeV, 16KW 200 mA dc, 250 kHz Short pulse, width 1 ns	Li(p, n) Neutron energies 1-200 keV Pulsed beam ~10^7 n/cm^2/s @ 0.8m Straight beam ~10^8 n/cm^2/s	Nuclear astrophysics Materials research, radiography Detector development Education

The NEPIR Facility of LNL

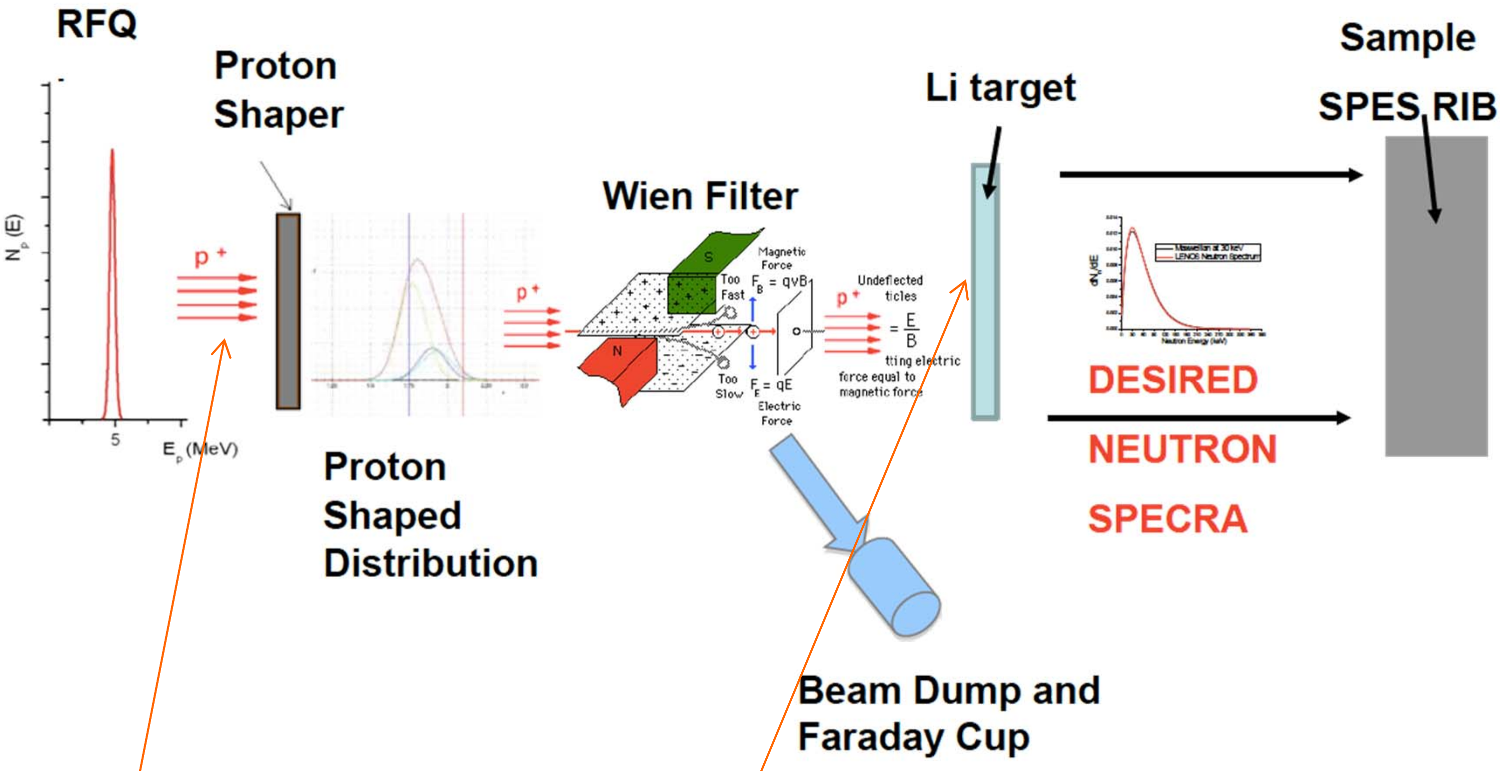
Italy



Proton cyclotron	Target station	Major activities
35-70 MeV, up to 500μA CW (can be converted to Pulsed mode)	X(p,n), X=Li. Be, Pb, W, & Ta Neutron energies 1-200 keV $10^5 – 10^6$ n/cm^2/s or $10^{13} – 10^{14}$ n/s	Fast neutron irradiation, SEES tests Cross section measurements, nuclear data for ADS Imaging, materials analysis

The Legnaro NeutrOn Source (LENOS)

Italy



RFQ

Proton Shaper

Wien Filter

Li target

Sample

SPES RIB

DESIRED NEUTRON SPECRA

Proton Shaped Distribution

Beam Dump and Faraday Cup

Proton RFQ	Target station	Major activities
5 MeV, 16KW 50 mA, 20 Hz CW (1st phase), pulsed (2nd phase), width 2 ns, 125 kHz	Li(p, n) No moderator 3x10^{14} n/s (calc.)	Nuclear astrophysics, nuclear data Neutron activation, Imaging

Prospective CANS Projects Elsewhere

- The *Neutron Time-of-Flight (NTOF)* facility located at CERN Geneva, Switzerland
- The *Gaerttner Linear Accelerator (LINAC*) Laboratory at RPI, USA
- *DANCE* (http://wnr.lanl.gov/dance/), Los Alamos
- The *Oak Ridge Electron Linear Accelerator (ORELA)*
- *Frascati Neutron Generator*, ENEA-Frascati
- Neutron time-of-flight experiments at *ELBE*
- *keV-neutron capture cross sections* at TIT, Japan
- *TSL*, the Uppsala (n,p) facility
- *Frascati Neutron Generator (FNG)*, Italy
- *IThemba* neutron source, South Africa
- The *Tiara neutron source*, Japan
- THE *ELBE-Project* AT Dresden-Rossendorf

Education and Mentoring

1 Exchange of scientists, engineers and students
2 Include CANS in neutron schools and workshops
3 Books about CANS:

Neutron Scattering Applications and Techniques (Springer)
Series Editors: Ian Anderson, Alan Hurd, & Robert McGreevy

Upcoming volumes:

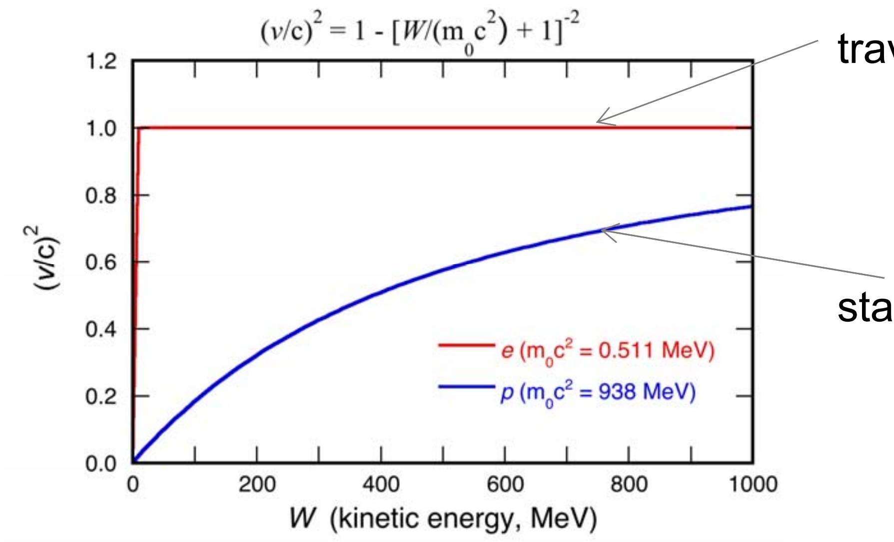
Compact Accelerator Driven Neutron Sources: Physics, Technology and Applications
Editors: David V. Baxter (Indiana U), Michihiro Furusaka (Hokkaido U), & Chun Loong

Neutron Experimental Methods in Cultural Research
Editors: Nikolay Kardjilov (Helmholtz-Zentrum Berlin) and Giulia Festa (U Rome)

How Do CANSs work?

Accelerator Structures

Accelerators: Electron Versus Ions



travelling wave structures

standing wave structures

e-linac: acceleration to $v \approx$ c achieved near the injection entrance, remaining accelerator structures are identical ➔ simple

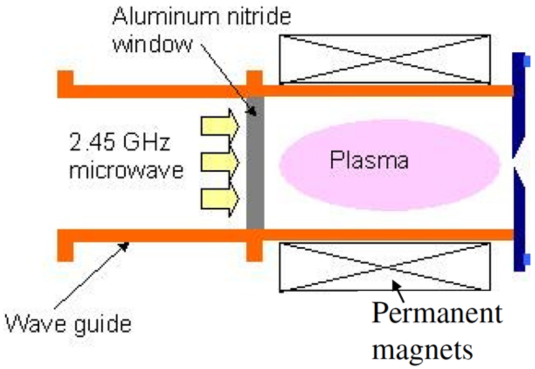
p (and ion) accelerators: need different accelerator structures to maximize the energy transfer to the particles from the accelerating fields (condition of synchronicity) ➔ tricky & costly

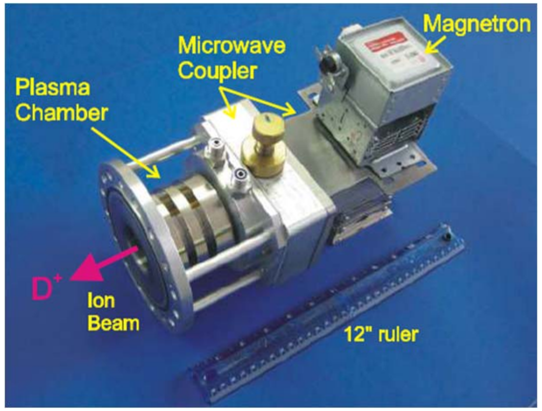
Another important distinction is *synchrotron radiation* emitted by an ultra-relativistic particle (along a bent orbit); it affects an electron beam much more than a proton beam ($\sim m_0^{-4}$).

CANS has a merit of avoiding the complex and expensive accelerator structures (and shielding). Here, only consider ion sources, and the basic linear accelerator components.

Electron Cyclotron Resonance Ion Sources (ECRIS)

There are many kinds of ion sources. ECRIS makes use of a guiding microwave power to transfer energy to electrons which ionize the fed-in gas atoms, forming a plasma. A magnetic field B is applied to maintain a resonance condition for the confinement of the charges q at the angular cyclotron frequency $\omega = qB/\gamma m_0$



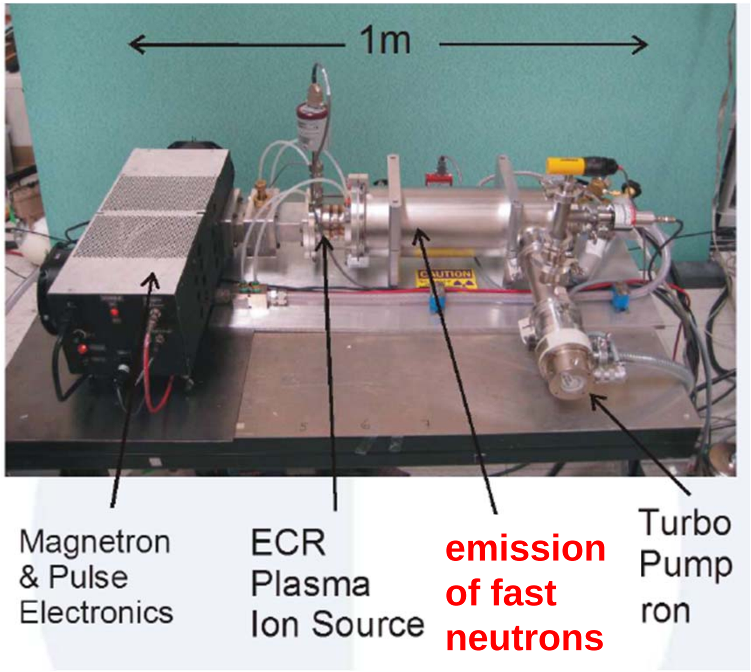


Ji *et al.* (2010)

2.45 GHz microwave (B=0.0875 T) is chosen for the compact setup. ECRIS forms the basis for **neutron generators** using the D-T & D-D reactions:

$$d + t \longrightarrow \alpha(3.5\text{MeV}) + n(14.1\text{MeV})$$

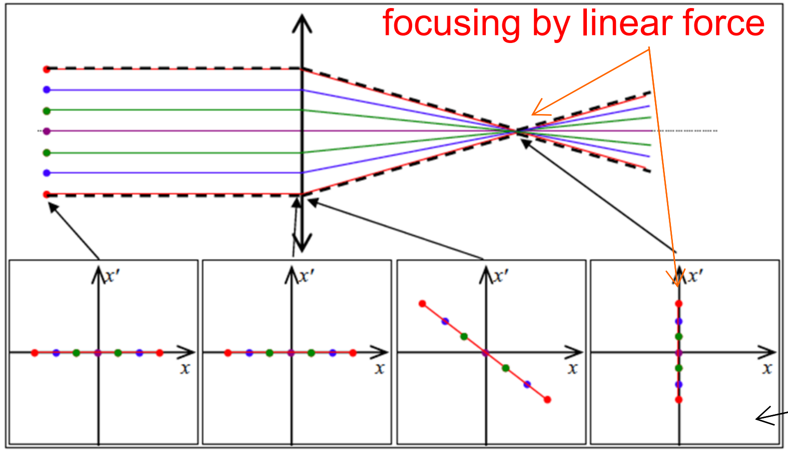
$$d + d \longrightarrow \alpha(0.866\text{MeV}) + n(2.4\text{MeV})$$

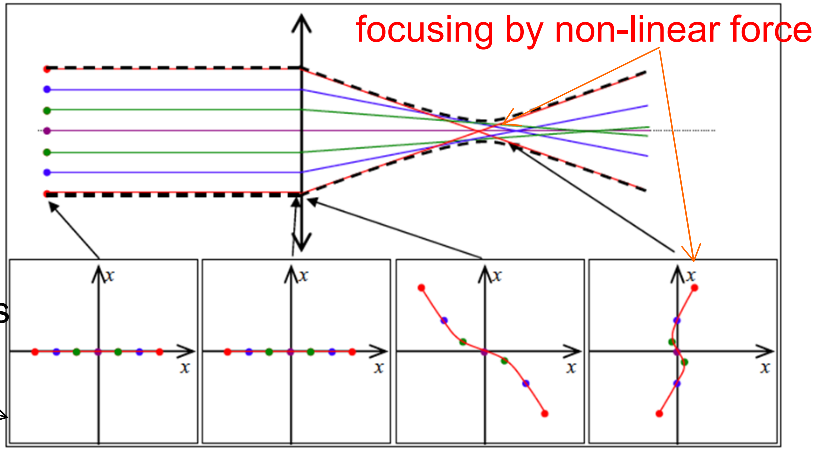


adelphi
TECHNOLOGY, INC.

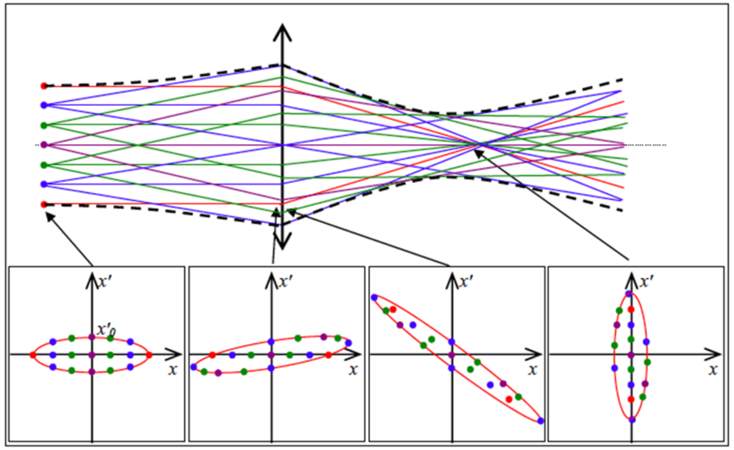
Emittance

The motion of a bunch of 10^6–10^{10} particles is represented in 6D-phase space: $(x, p_x=x', y, p_y=y', z, p_z=z')$. We are interested in the projection of the hyper-ellipsoid on the longitudinal and transverse planes.





laminar beams
emittance = 0



emittance > 0

Liouville theorem

Emittance is conserved under conservative forces (including non-linear forces); it depends only on the geometrical dimensions of this phase space.

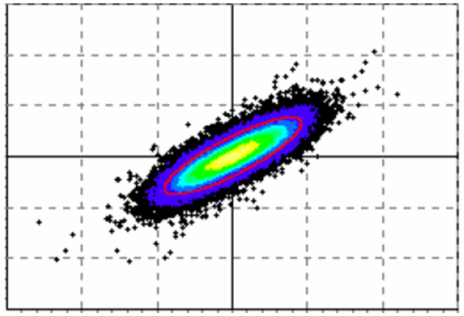
The Liouville theorem works against you if you want to inject more particles, say protons, into a phase space of the same beam such as in a storage ring.

This is circumvented by injecting *H*⁻ ions on top of the proton beam and then convert *H*⁻ to *p* by stripping off its electrons.

Pichoff (2005) CERN Acc. School

Emittance of a Real Beam: N Particles in Each Bunch

The emittance represents the phase-space volume occupied by the particles in a bunch of the beam. The higher the emittance, the lower the capacity to transport the beam parallel over a long distance and to focus it to a small size.



$$\langle w\rangle = \frac{1}{N}\sum_{i=1,N} w_i, \quad w=\{x,y,z\} \qquad \text{average position}$$

$$\langle w'\rangle = \frac{1}{N}\sum_{i=1,N} w'_i, \quad w'=\{x',y',z'\} \qquad \text{average slope}$$

$$\tilde{w} = \sqrt{\frac{1}{N}\sum_{i=1,N}\left(w_i-\langle w\rangle\right)^2}; \quad \tilde{w}' = \sqrt{\frac{1}{N}\sum_{i=1,N}\left(w'_i-\langle w'\rangle\right)^2} \qquad \text{rms size and divergence}$$

$$\tilde{\varepsilon}_w = \sqrt{\tilde{w}^2\tilde{w}'^2 - \left\langle\left(w-\langle w\rangle\right)\cdot\left(w'-\langle w'\rangle\right)\right\rangle^2} \qquad \text{rms emittance, dimension} \sim \text{surface in the } (w,w') \text{ space}$$

$$\tilde{\varepsilon}_{wn} = \beta\gamma\tilde{\varepsilon}_w \qquad \text{normalized rms emittance due to longitudinal acceleration}$$

Comparing the *twiss parameters* (derived from $\tilde{\varepsilon}_{wn}$) with the *Courant-Snyder parameters*: **Beam matching**

For low-E, high current beams – normally the case for CANS, the *space charge forces* – Coulomb repulsion between particles within a bunch, if not restrained, will lead to defocusing of the beam. Furthermore, a low-E beam cannot take advantage of the *phase damping effect* – the shortening of bunching length in the longitudinal plane that occurs to a relativistic beam.

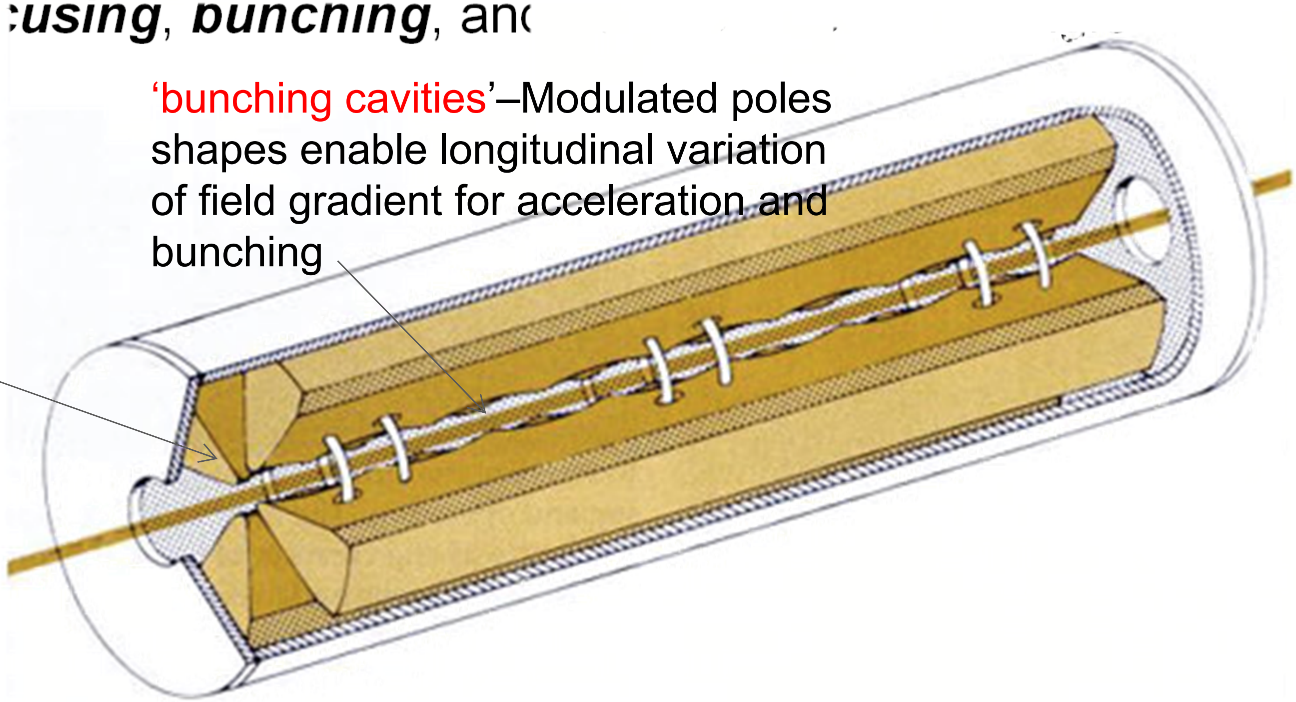
The job of an accelerator is to effectively provide controlled manipulations of the beam so as to achieve the designated energy (and time structure) in conjunction with an acceptable emittance.

Pichoff (2005) CERN Acc. School

Low β Structure: Radio Frequency Quadrupole (RFQ)

Kapchinski & Teplyakov (1970). An RFQ linac provides combined functions of ***electric focusing***, ***bunching***, and

resonator.



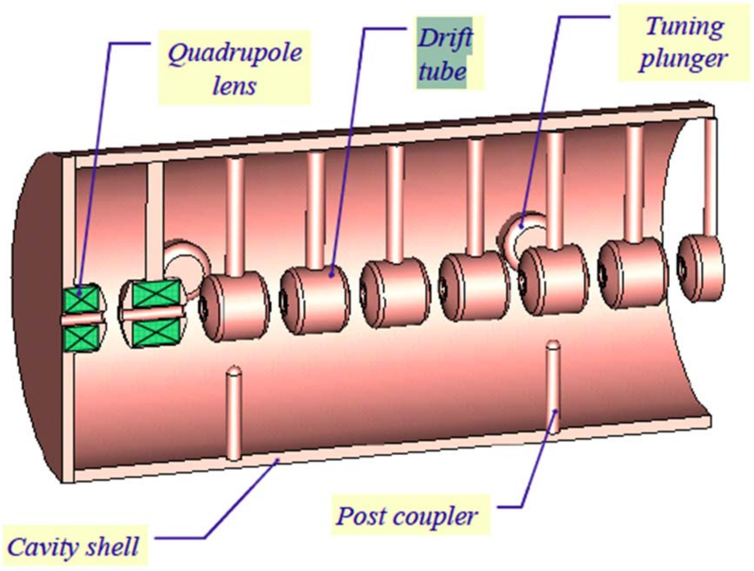
Four vanes quadrupolar resonator provides transverse electric focusing

‘bunching cavities’–Modulated poles shapes enable longitudinal variation of field gradient for acceleration and bunching

Accelerate protons from ~50 keV to ~3 MeV over ~3m.

Technology: precision machining of copper or copper plated parts, furnace brazing, welding and gasket mounting,…

Low β Drift Tube Linacs



In a cavity of cylindrical geometry, particles drift inside Faraday tubes and accelerate cross the gaps, driven by constant frequency (*f*) RF power supply under an optimized TM_{mnp} mode.

$$\left.\begin{matrix}\text{peak electric field}\\ \text{RF efficiency}\end{matrix}\right\}\sim\sqrt{f};\qquad \left.\begin{matrix}\text{cell length}\\ \text{accelerator dimensions}\\ \text{tolerance}\\ \text{focusing effectiveness}\end{matrix}\right\}\sim 1/f$$

High RF frequency → compact structure, high efficiency but demanding high precision & cost, and strong focusing condition

Technology: High-power, high-frequency RF amplifiers.

Gerigk (2010), CERN Acc. School

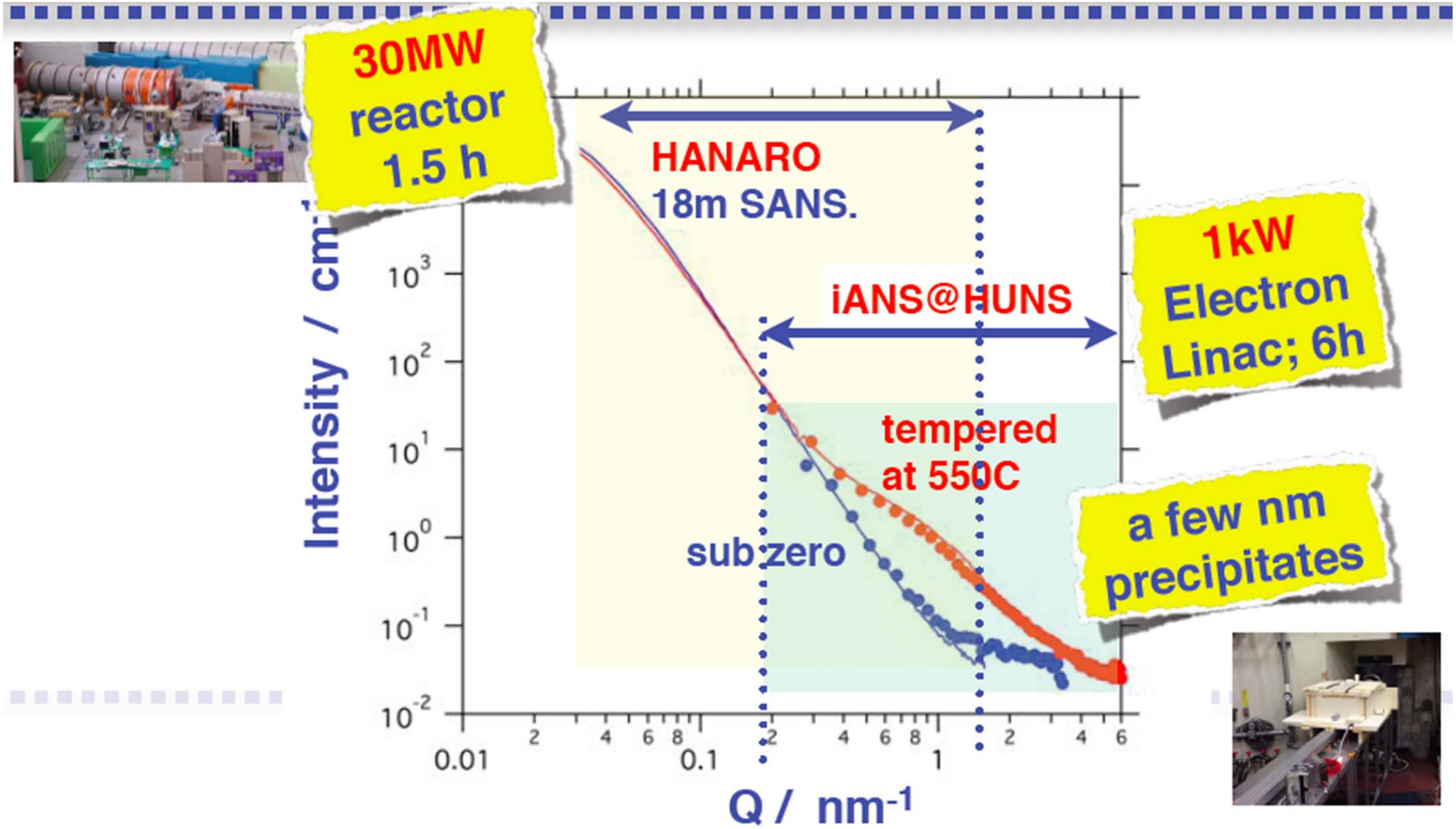
Conclusions about CANS Accelerators

- ✧ The attribute of compactness and low energy of CANS leads to significant saving in construction and operation costs.
- ✧ The entire architecture is amenable to prototyping, multiplexing, and reconfiguration for proof-of-principle to specialized R&D.
- ✧ The accelerator technology of compact neutron sources is mature and relatively straightforward.
- ✧ The linac-based structure implies a long-pulse time structure (except for *e*-linac machines). Bunch compression for low-E beams may be challenging.
- ✧ CANS shares the target-moderator design and beamline instrumentation common to all pulsed sources thereby offering collaborative R&D opportunities to the overarching community.

Neutron Applications of CANS

Examples of Interdisciplinary Research

Small-Angle Scattering (SANS): Well Suited for CANS



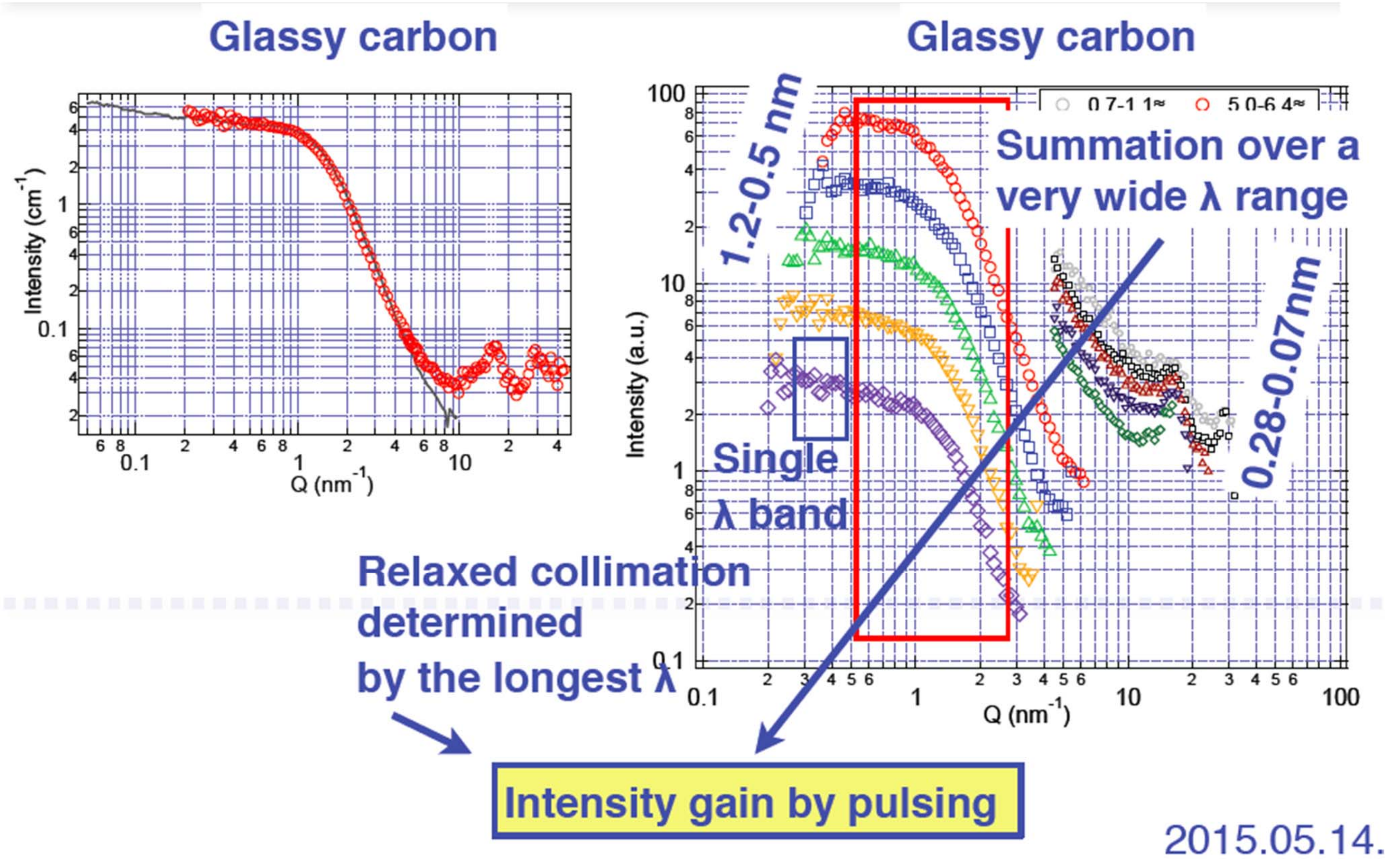
30MW reactor 1.5 h

1kW Electron Linac; 6h

a few nm precipitates

Furusaka (2015), UCANS-V

Small-Angle Scattering (SANS): Well Suited for CANS



Glassy carbon

Glassy carbon

1.2-0.5 nm

Summation over a very wide λ range

0.28-0.07nm

Single λ band

Relaxed collimation determined by the longest λ

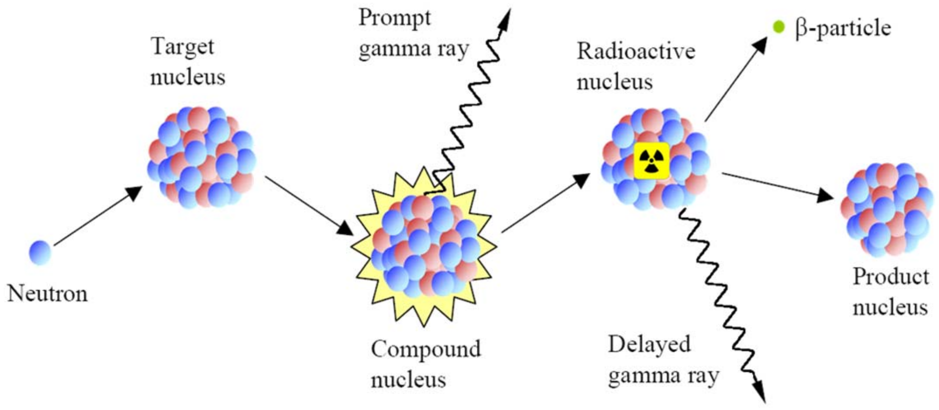
Intensity gain by pulsing

2015.05.14.

Furusaka (2015), UCANS-V

Imaging & Radiography: Beyond Conventional Approaches

Combine tomography with thermal-neutron-induced γ-ray imaging (PGA-CT):
Allow 3D elemental analysis



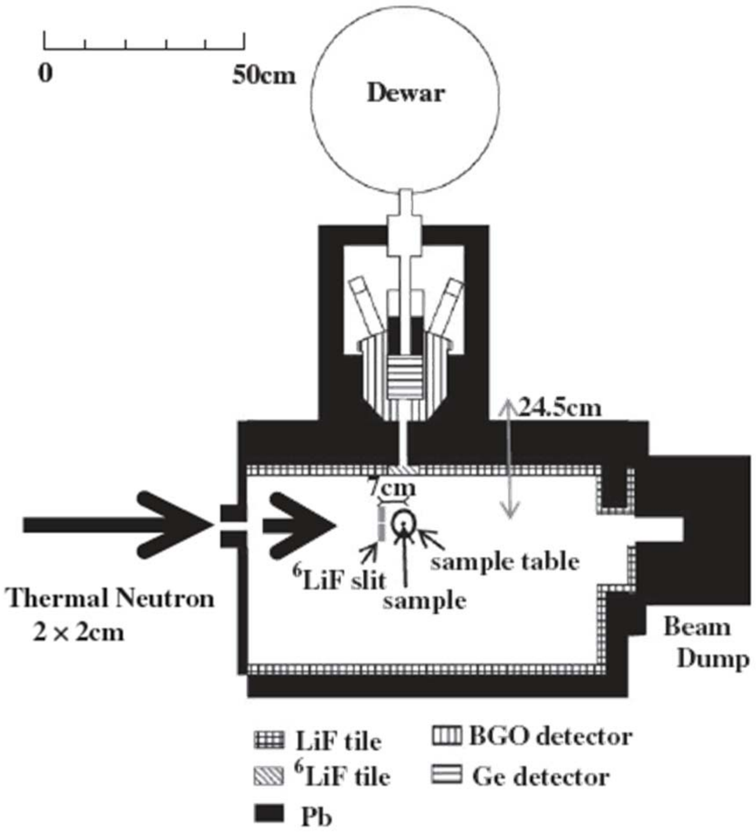


Fig. 1. Schematic view of experimental setup.

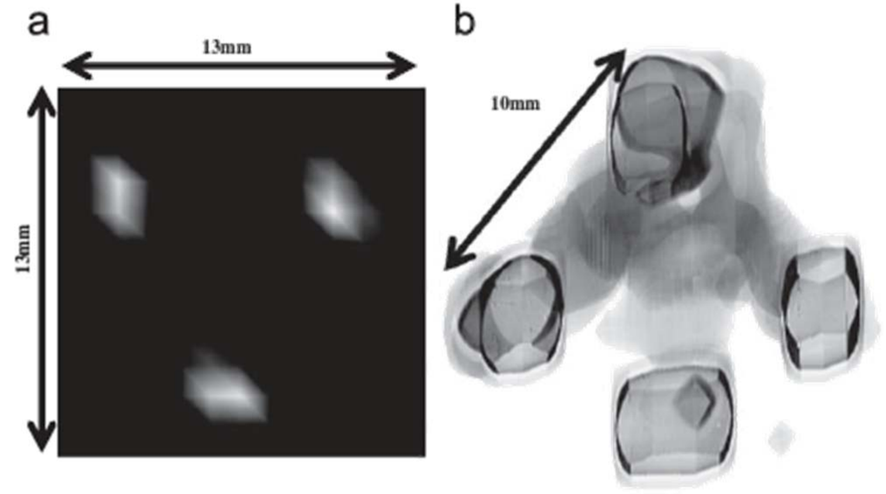


Fig. 5. The reconstruction images for a Cd sample in the form of a three-sided pyramid of 1 cm using the computerized tomography program "NIPPON". (a) A slice figure on the bottom of the sample in the X–Z plane. (b) A 3-D elemental image made by accumulations of slice figures.

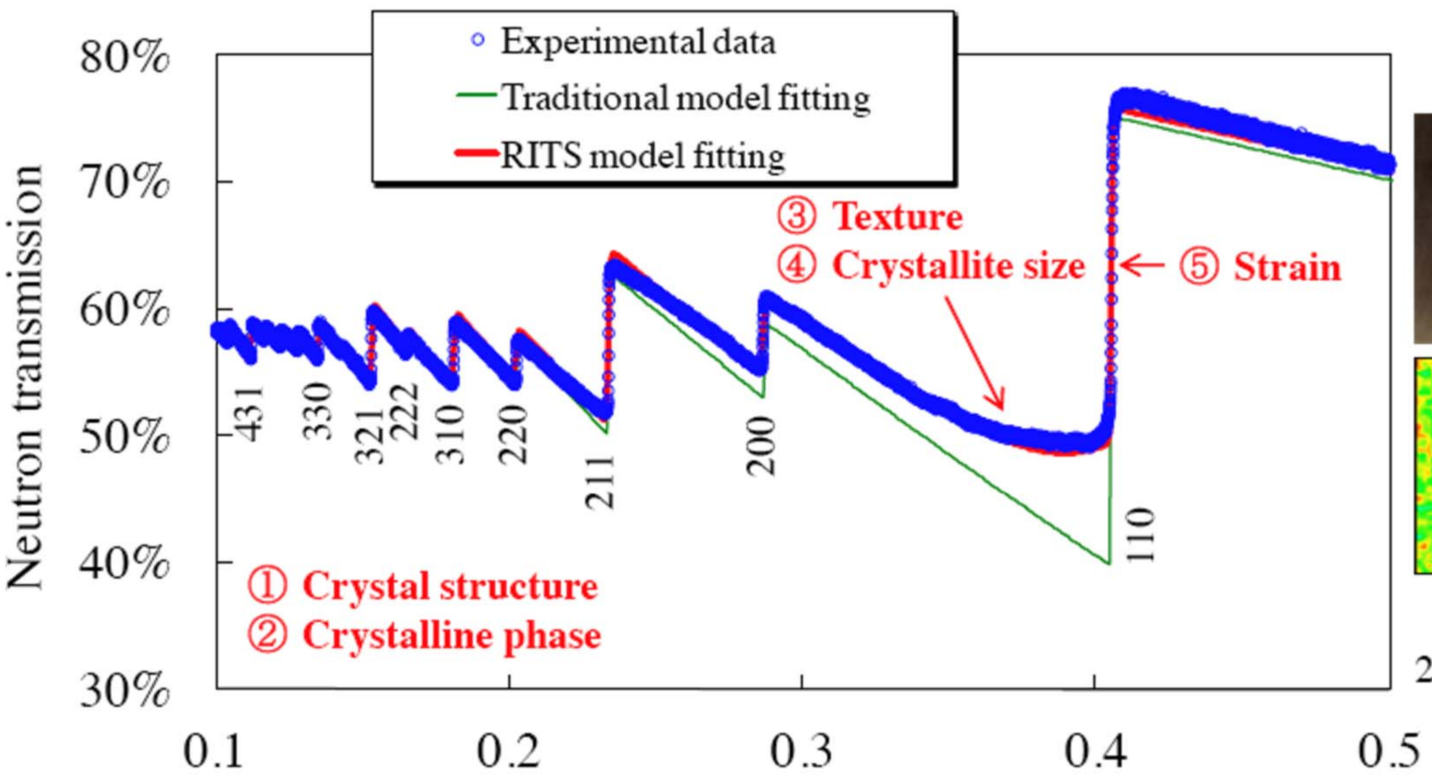
Segawa 2009

Imaging & Radiography: Beyond Conventional Approaches

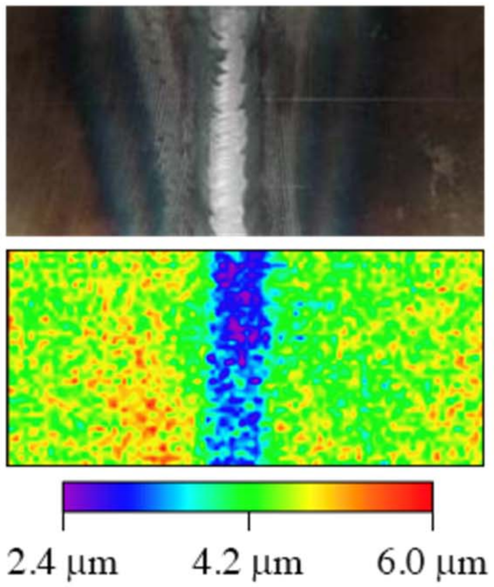
Combine imaging with crystal diffraction: Rietveld imaging transmission spectra (RITS)

Allow concurrent analysis of crystal structures, crystalline phases, crystallite sizes, texture, and strain

Bragg edge transmission of α-Fe



Quantitative imaging of crystallite size by the RITS code

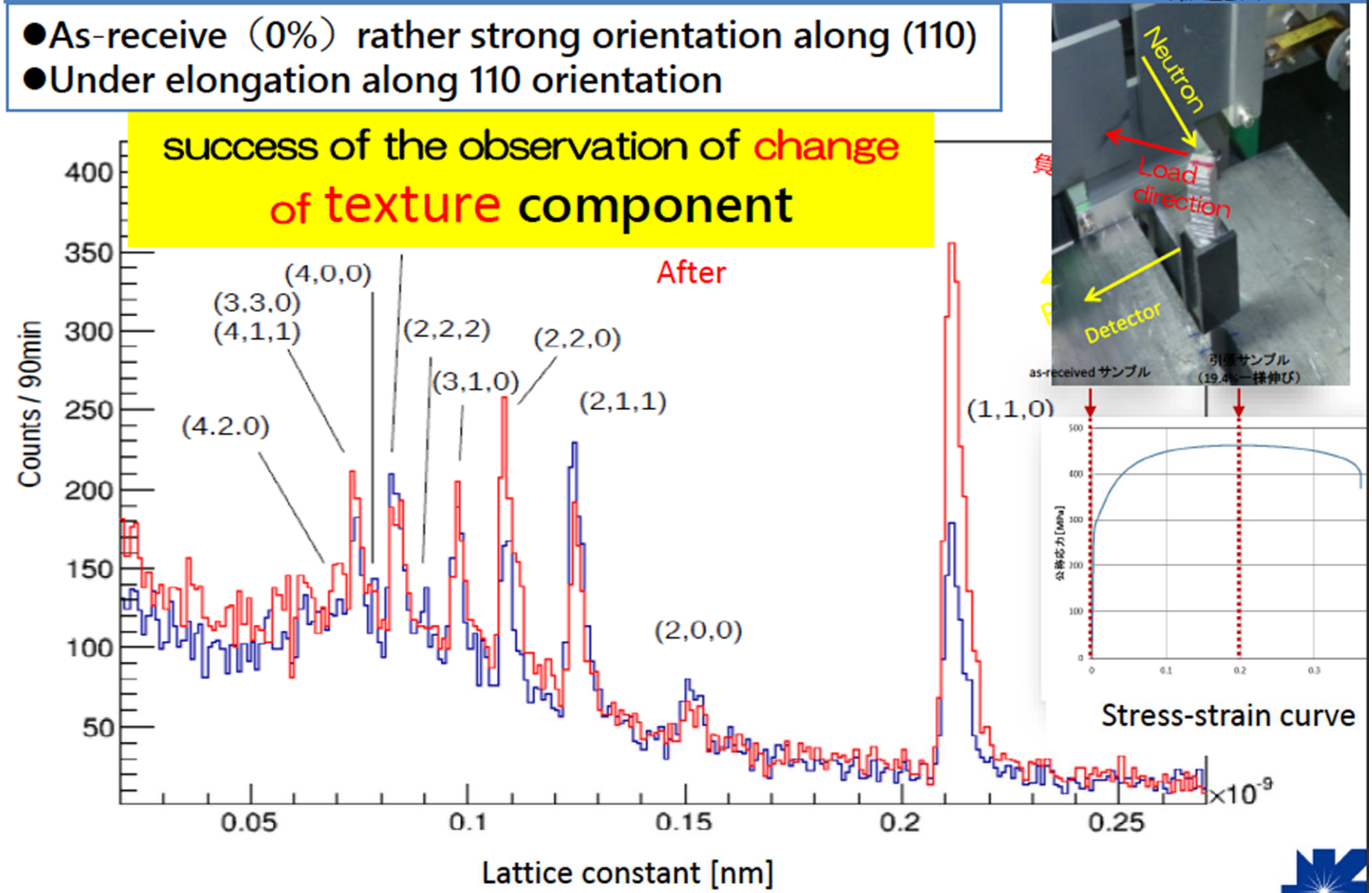


Sato 2011

Success of the observation of texture @ RANS

JAEA H. Suzuki,
RIKEN Takamura,
Y.IKEDA

- As-receive（0%）rather strong orientation along (110)
- Under elongation along 110 orientation



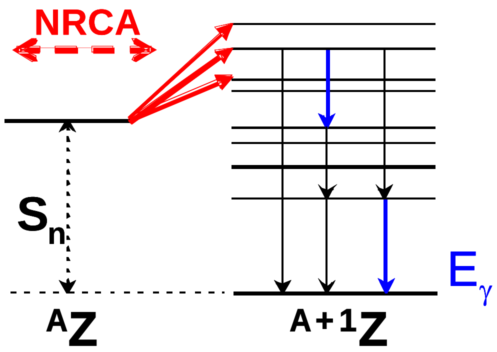
success of the observation of change of texture component

Stress-strain curve

Otake (2015), UCANS-V

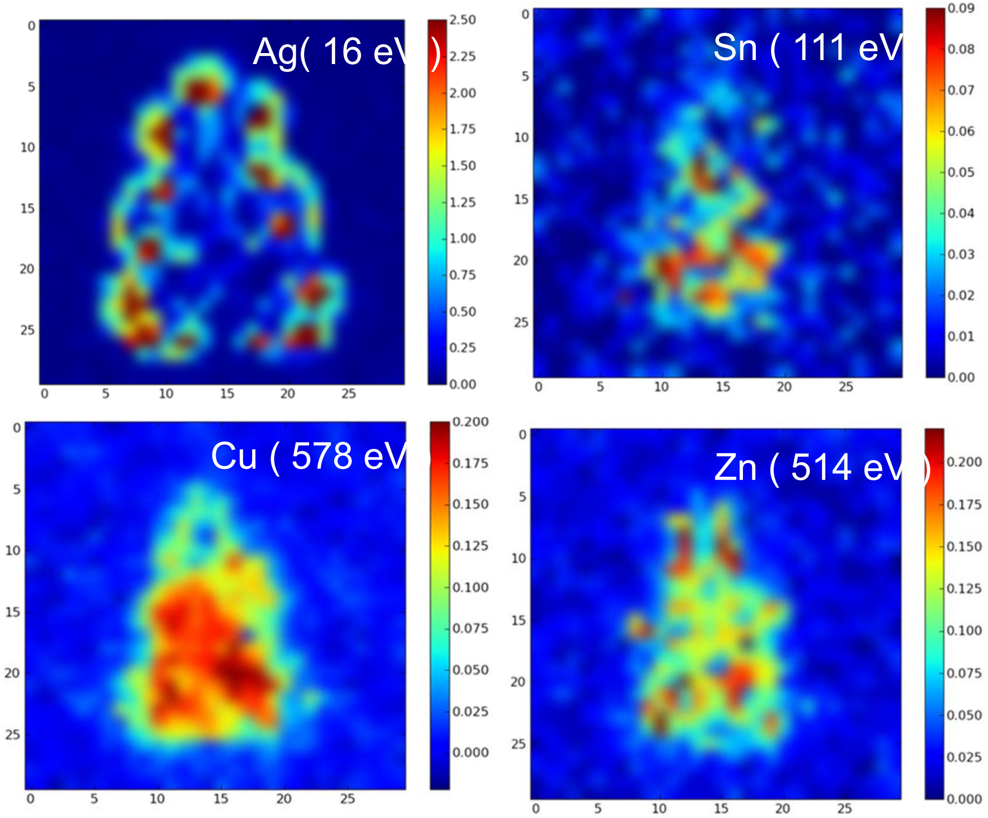
Imaging & Radiography: Beyond Conventional Approaches

Combine imaging with epithermal neutron resonance capture analysis (NRCA):
Allow elemental analysis, significant to archaeometry: high sensitivity to Cu, Sn Zn, As, Sb, Ag, Au, Pb,…



Original belt mount
Hungarian National
Museum, Budapest

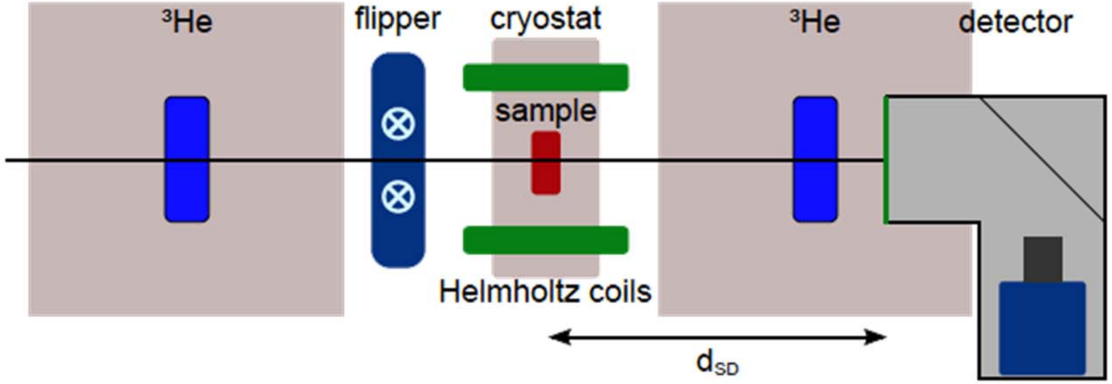
Andreani 2012



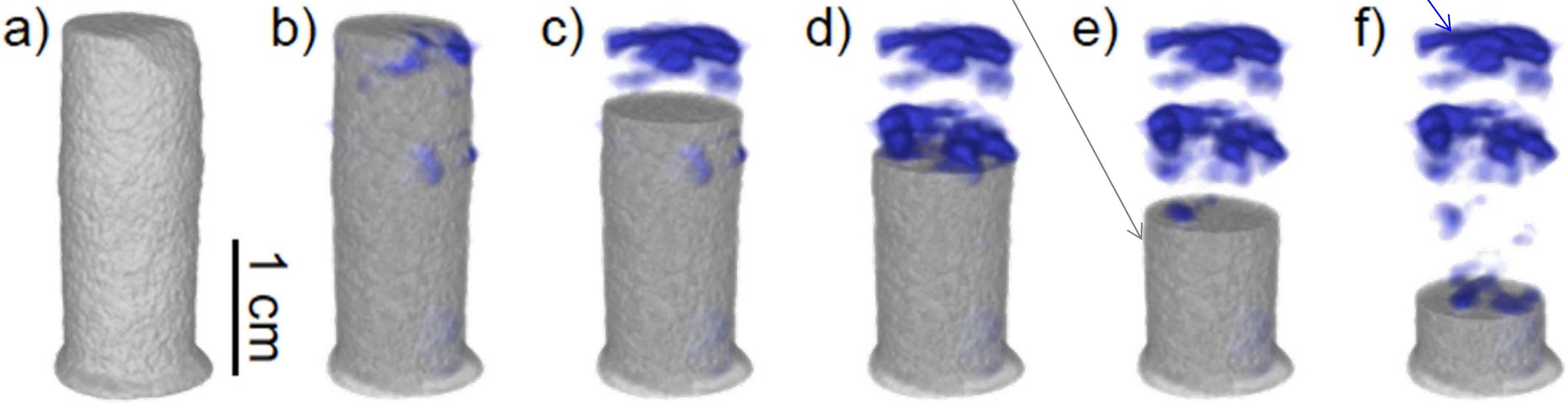
Magnetic Structures: Beyond Conventional Approaches

Combine imaging with polarization analysis of magnetic diffraction using polarized neutrons

Allow fundamental studies of quantum criticality, magnetic inhomogeneity in single crystals by depolarization imaging

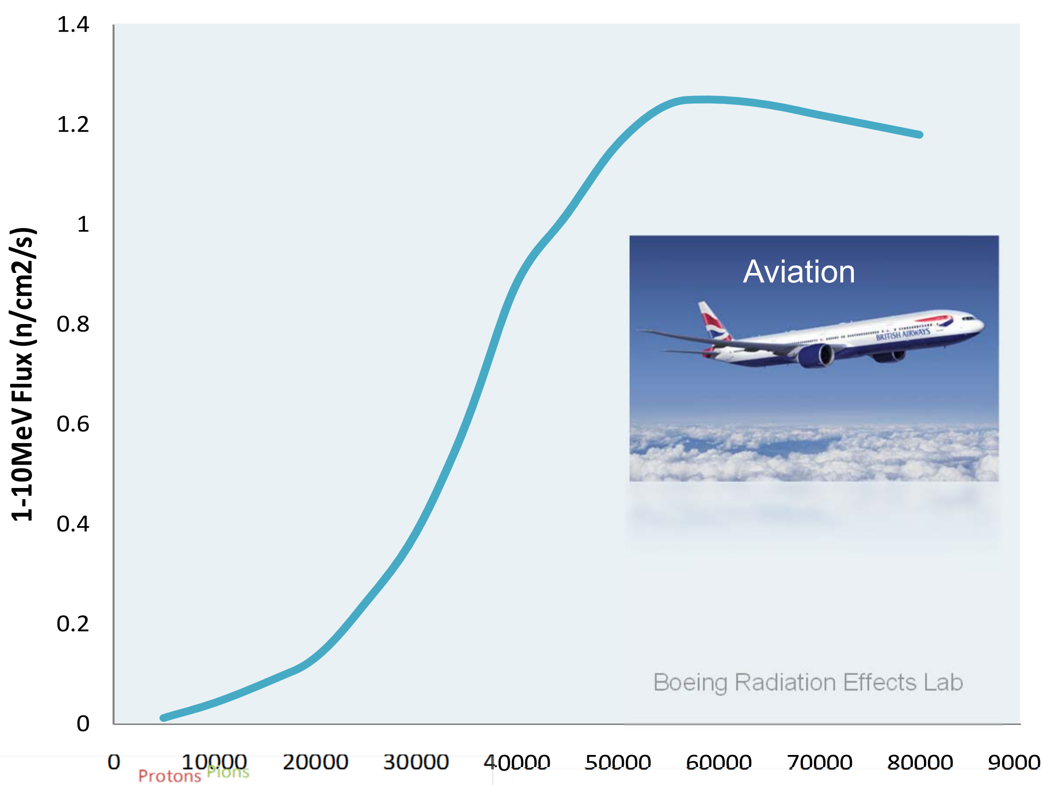


$Pd_{1-x}Ni_x$ single crystal x=2.67%, T = 8K



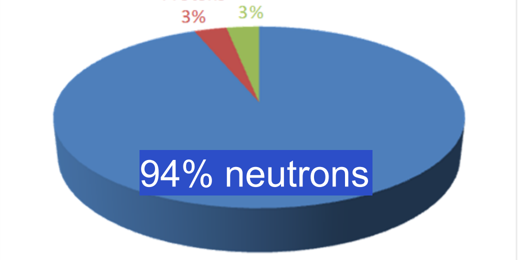
Schulz 2010

Neutron SEE is a Serious Threat at High Altitude & at Sea Level

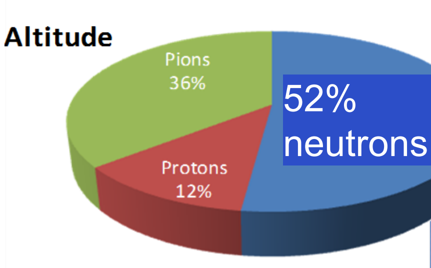


Boeing Radiation Effects Lab

Altitude

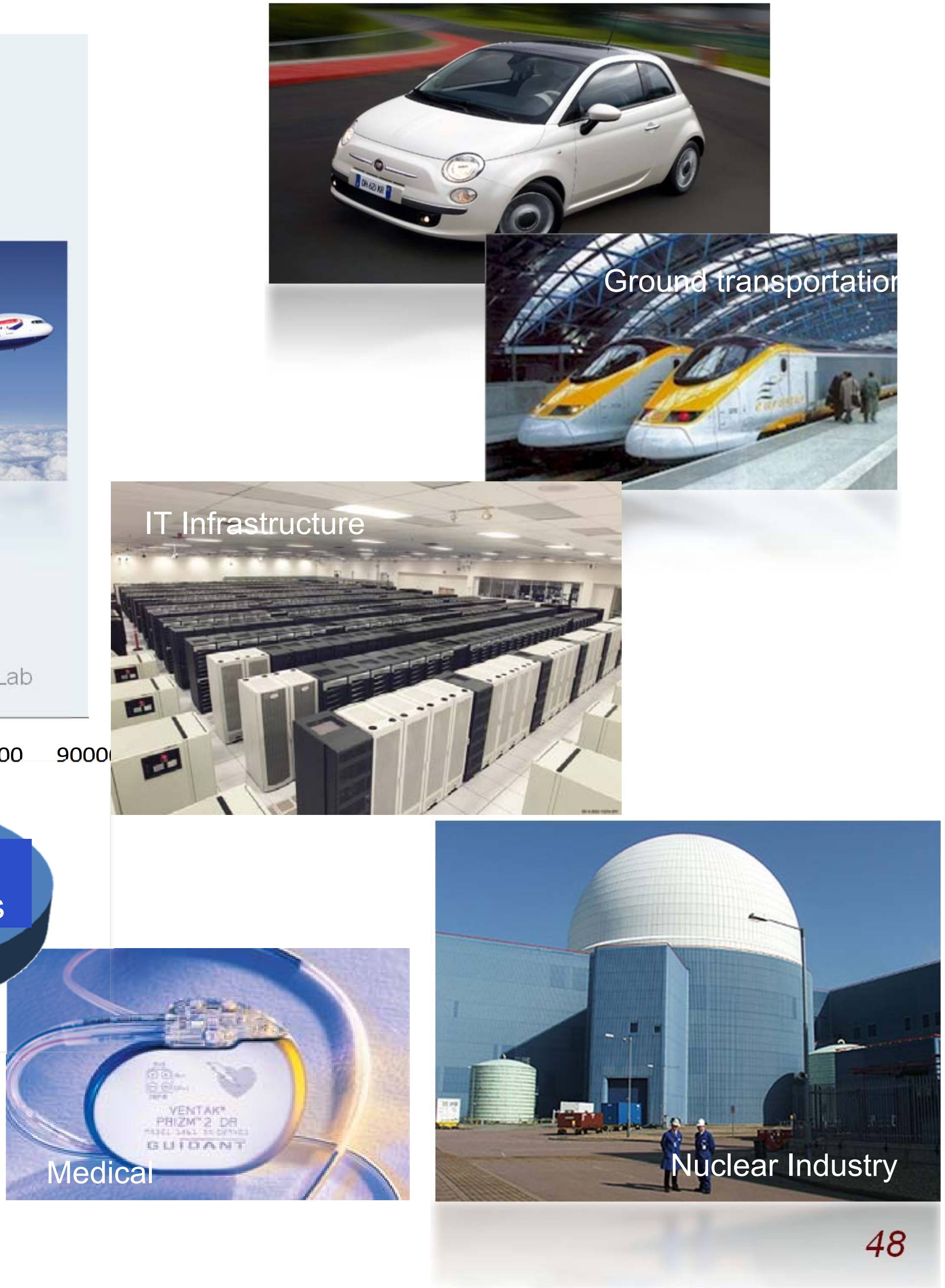


Sea Level



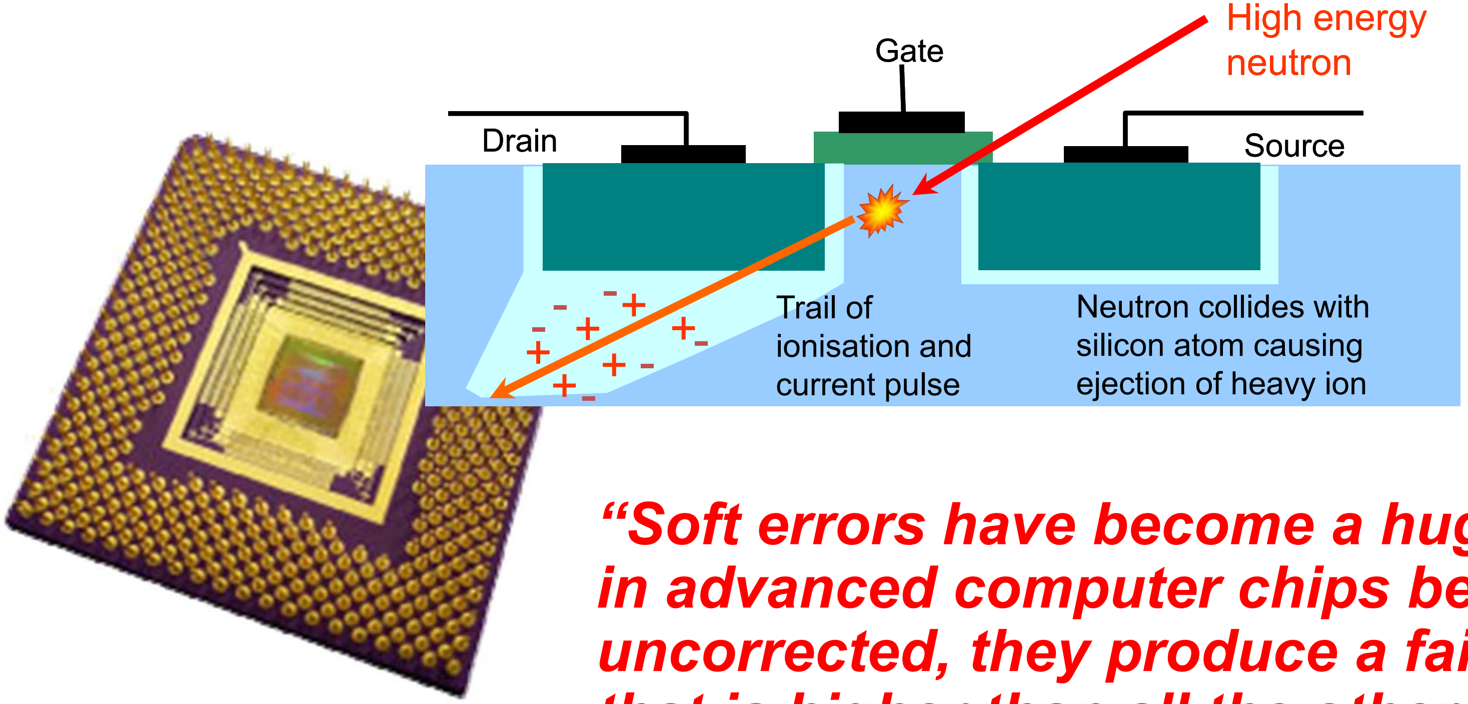
32,000 ft

Zilegler 1996



Neutron Impact on Industry and Life

Single Event Effects (SEE): A single energetic particle (neutron) strikes sensitive regions of an electronic device, e.g., logic or support circuitry, memory cells, registers, etc., disrupting its normal function, usually causing non-destructive soft errors.

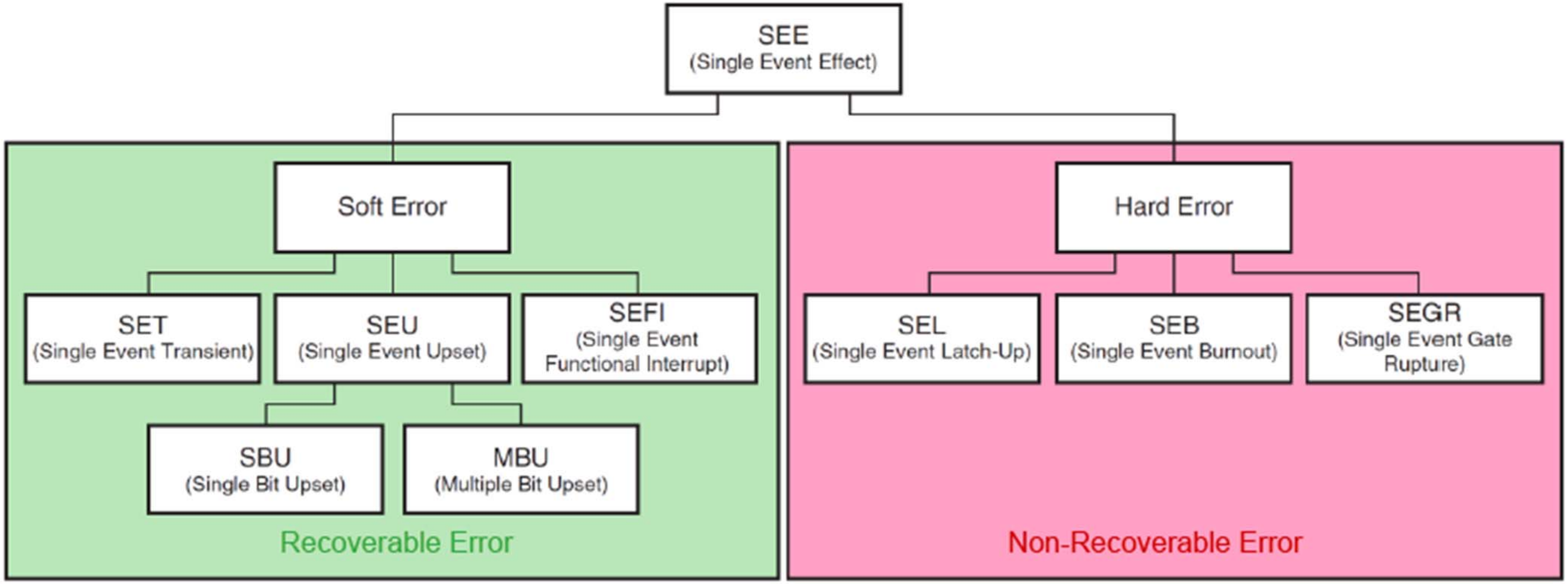


"Soft errors have become a huge concern in advanced computer chips because, uncorrected, they produce a failure rate that is higher than all the other reliability mechanisms combined!"

.......R. Baumann, IEEE-TDMR, 2005

Frost 2011

A Single Event Effect (SEE) is when a highly energetic particle present in the environment, strikes sensitive regions of an electronic device disrupting its correct operation


SEE
(Single Event Effect)

Soft Error

SET
(Single Event Transient)

SEU
(Single Event Upset)

SEFI
(Single Event Functional Interrupt)

SBU
(Single Bit Upset)

MBU
(Multiple Bit Upset)

Recoverable Error

Hard Error

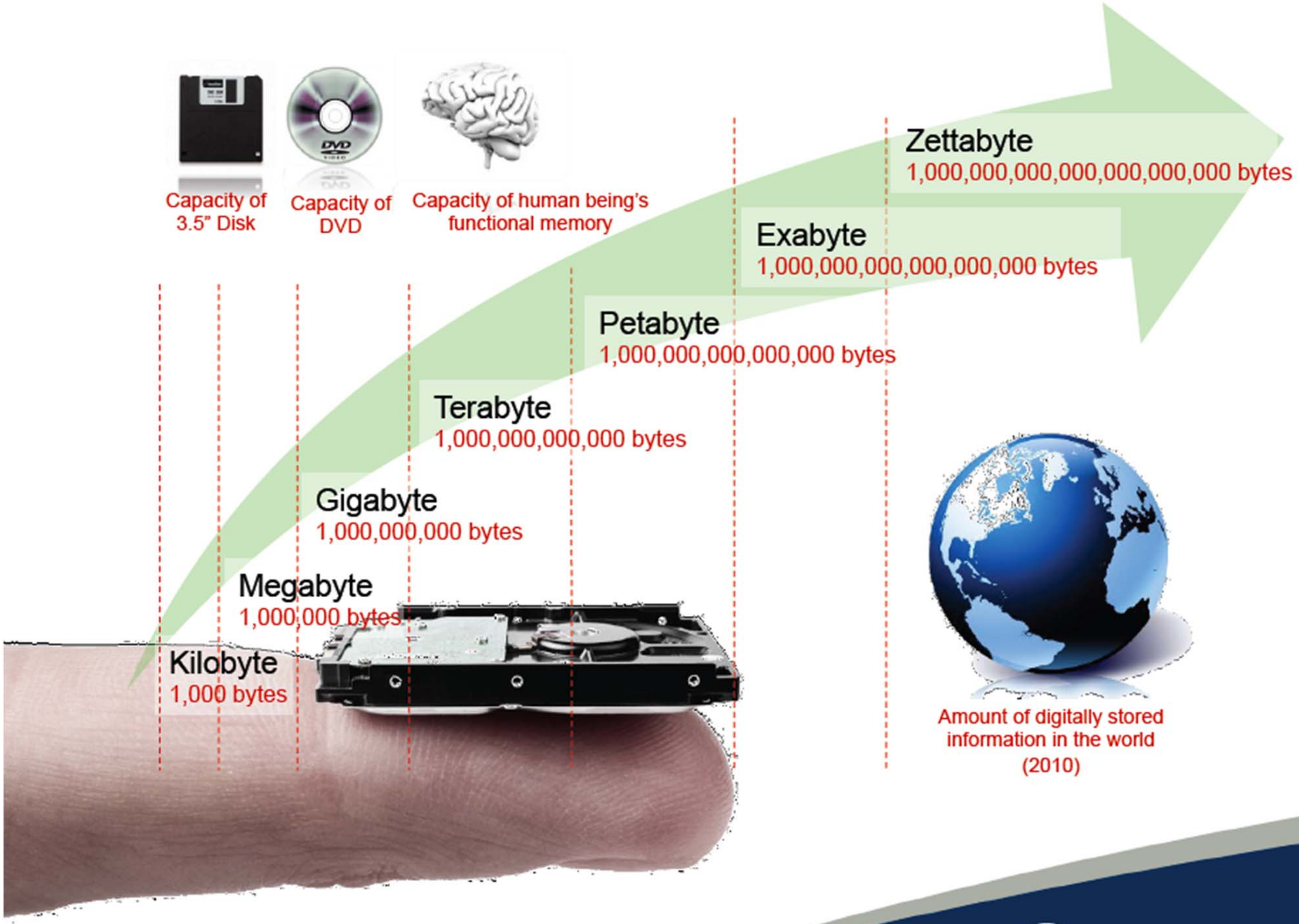
SEL
(Single Event Latch-Up)

SEB
(Single Event Burnout)

SEGR
(Single Event Gate Rupture)

Non-Recoverable Error

Diagram Courtesy: Xilinx



Capacity of 3.5" Disk

Capacity of DVD

Capacity of human being's functional memory

Kilobyte
1,000 bytes

Megabyte
1,000,000 bytes

Gigabyte
1,000,000,000 bytes

Terabyte
1,000,000,000,000 bytes

Petabyte
1,000,000,000,000,000 bytes

Exabyte
1,000,000,000,000,000,000 bytes

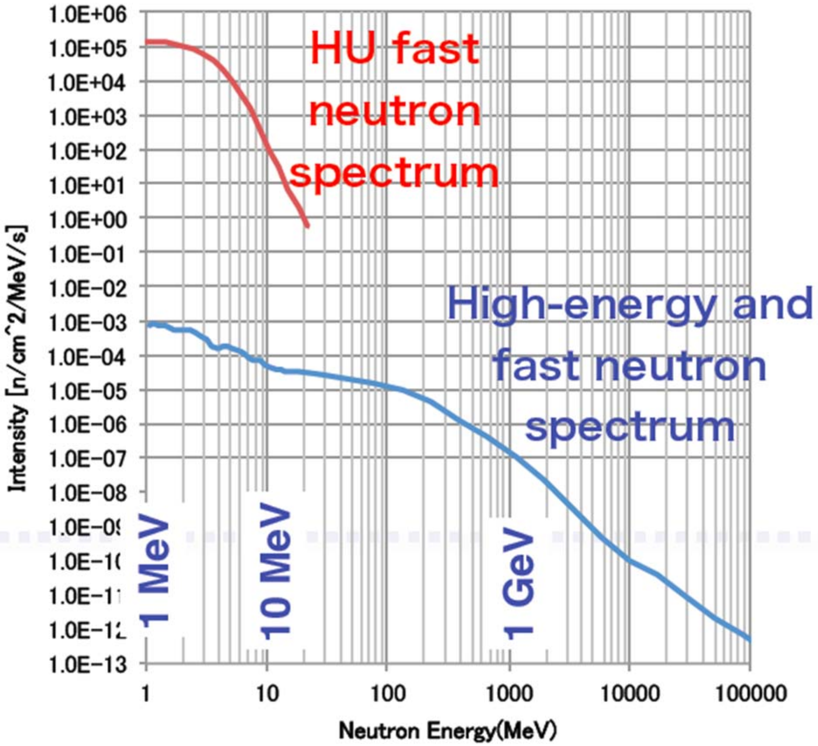
Zettabyte
1,000,000,000,000,000,000,000 bytes

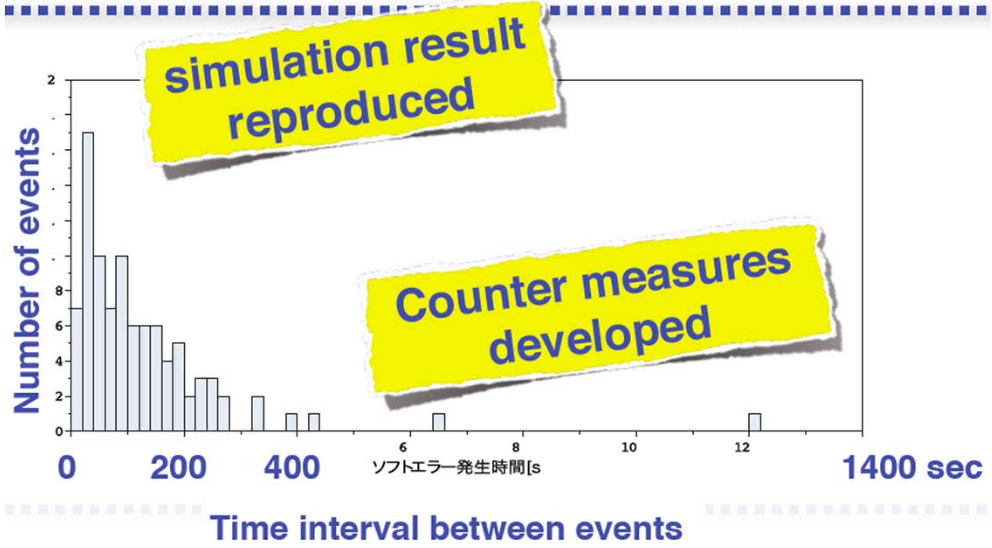
Amount of digitally stored information in the world (2010)

Source: Cisco

Measurements of Soft-Error Counts in Electronics At HUNS

HOKKAIDO UNIVERSITY





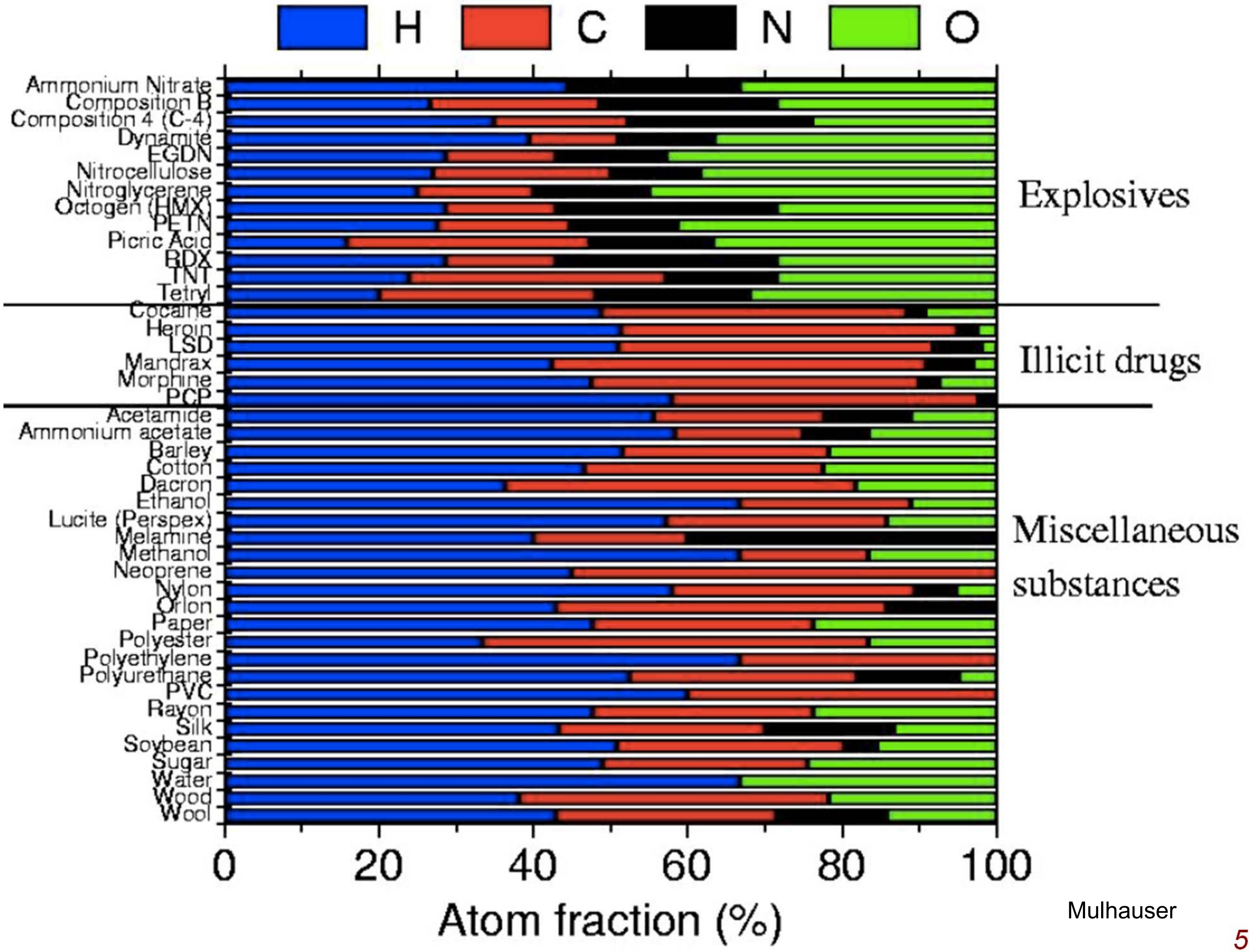
Furusaka (2015), UCANS-V

Neutron Interrogation of Concealed Substances: Explosive

Desirable capabilities

- ✧ Remote detection
- ✧ Non-intrusive
- ✧ High sensitivity (chemical density, 3D volumetric rendering)
- ✧ Materials specific (precise, minimize false alarms)
- ✧ Rapid
- ✧ Flexible (portable, on-site deployment,…)
- ✧ Automatic

Chemical Composition of Different Materials



Mulhauser

Aim to be More Quantitative Than N/C Ratio Detection

	Materials	C	H	N	O	P	F	Cl	S	N/H	N/C
Explosives	C4	21.9	3.6	34.4	40.1	0	0	0	0	10	2
	TNT	37	2.2	18.5	42.3	0	0	0	0	8	1
	PETN	19	2.4	17.7	60.8	0	0	0	0	7	1
	AN	0	5	35	60	0	0	0	0	7	∞
Chemical agents	Sarin	34.3	7.1	0	22.9	22.1	13.6	0	0	0	0
	VX	49.5	9.7	5.2	12	11.6	0	0	12	1	0
	CA	44.5	3.7	51.8	0	0	0	0	0	14	1
	HD	30.2	5	0	0	0	0	44.6	0	0	0
	Phosgene	12.1	0	0	16.2	0	0	71.7	0	NA	0
Benign	Water	0	11.1	0	88.9	0	0	0	0	0	0
	Paper	44	6	0	50	0	0	0	0	0	0
	Plastic	86	14	0	0	0	0	0	0	0	0
	Salt	0	0	0	0	0	0	60	0	NA	NA

Explosives are rich in N and O but poor in H and C

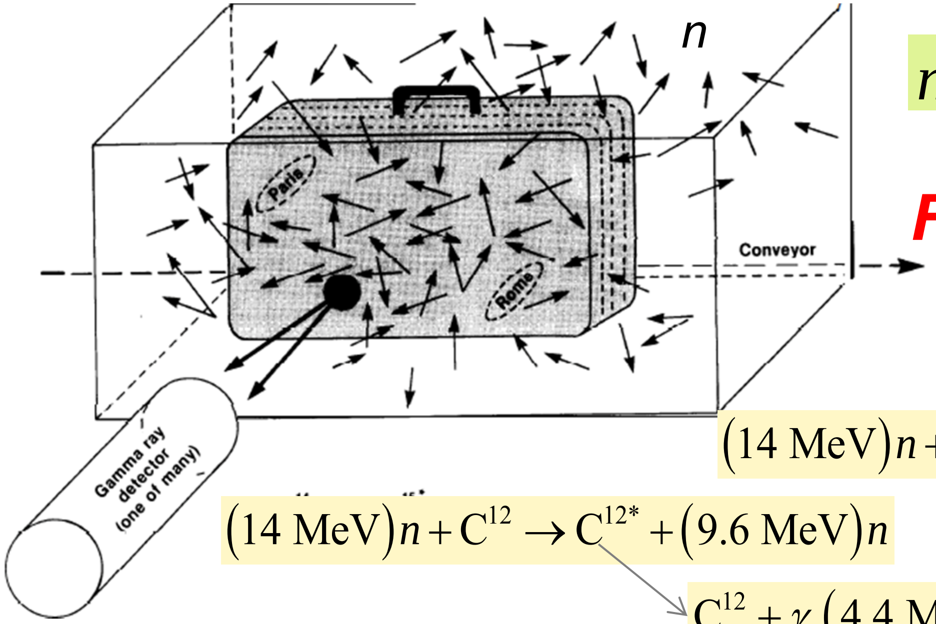
Gozani 2005

"Neutron in Gamma Out" Methods (1)

Thermal Neutron Analysis (TNA): In TNA the object is irradiated by slow (thermal) neutrons, which produce gamma-rays in reactions of radiative capture with the nuclei of chemical elements constituting ES. e.g. N: 10.8 MeV H: hydrogen 2.23 MeV Cl: 7.50 and 6.11 MeV, etc.

Fast Neutron Analysis (FNA): The object is irradiated with a continuous flux of fast neutrons with energy above 8 MeV, which produce characteristic gamma-rays in inelastic scattering reactions with nuclei of C: 4.44, O: 6.13,.. N: 5.1 MeV. Detection of these secondary gamma-rays provides information about relative concentrations of carbon, oxygen and nitrogen in molecules of the inspected substance.

Neutron Resonance Attenuation (NRA): *A neutron radiography technique* measuring the areal density (density times thickness) of elements present in the interrogated object.



TNA

$$n + \mathrm{N}^{14} \to \mathrm{N}^{16*}$$

$$\mathrm{N}^{15} + \gamma\,(10.8\ \mathrm{MeV})$$

FNA

$$(14\ \mathrm{MeV})\,n + \mathrm{N}^{14} \to \mathrm{N}^{14*} + (8.9\ \mathrm{MeV})\,n$$

$$\mathrm{N}^{14} + \gamma\,(5.1\ \mathrm{MeV})$$

$$(14\ \mathrm{MeV})\,n + \mathrm{O}^{16} \to \mathrm{O}^{16*} + (7.9\ \mathrm{MeV})\,n$$

$$\mathrm{O}^{16} + \gamma\,(6.1\ \mathrm{MeV})$$

$$(14\ \mathrm{MeV})\,n + \mathrm{C}^{12} \to \mathrm{C}^{12*} + (9.6\ \mathrm{MeV})\,n$$

$$\mathrm{C}^{12} + \gamma\,(4.4\ \mathrm{MeV})$$

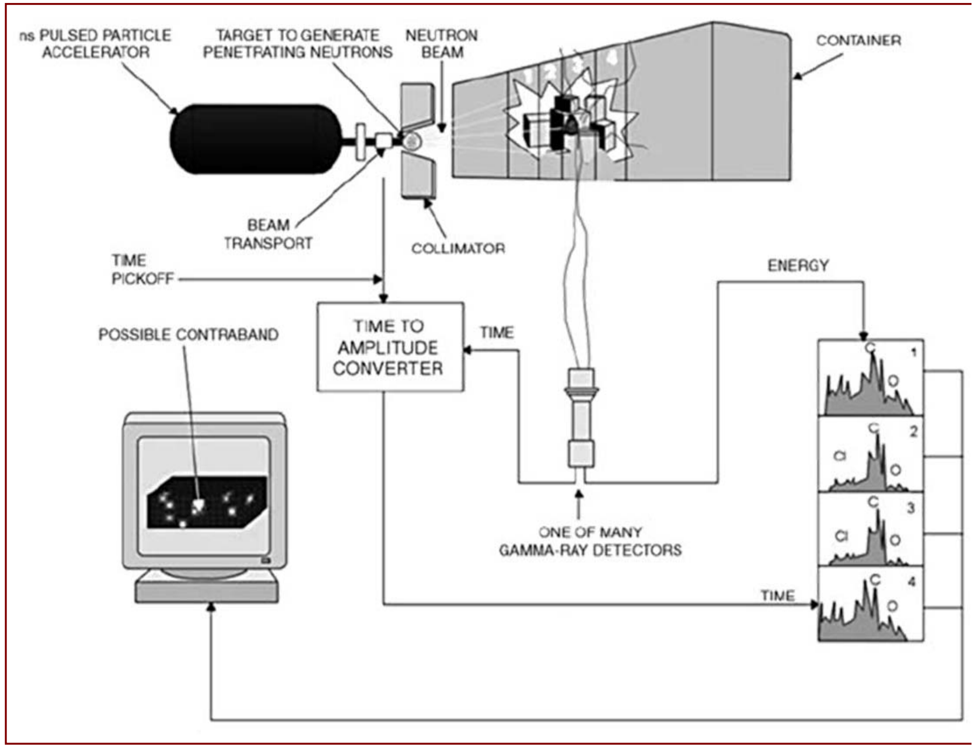
Grodzine 1990; Schubert 2006

“Neutron in Gamma Out” Methods (2)

Pulsed Fast Neutron Analysis (PFNA): Use pulsed neutron flux (with pulse duration of several nanoseconds) to irradiate the inspected object. This allows one to use time of flight information to determine the location of the ES inside the inspected volume. By using collimators for the neutron beam one can get a 3D distribution of carbon, oxygen and nitrogen in the investigated object.

Pulsed Fast and Thermal Neutron Analysis (PFTNA): PFTNA is a combination FNA and TNA.

Nanosecond Neutron Analysis / Associated Particles Technique (NNA/APT): Use d(t,α)n to produce fast neutrons in portable neutron generators, mono-energetic neutrons (E = 14 MeV) and α-particles (E = 3 MeV) are emitted simultaneously in opposite directions. Tag *n* with α to discriminate secondary γ. Background γ-rays that are not correlated in time with “tagged” neutrons are rejected by the data acquisition system. Use of position sensitivity of the α-detector and time-of-flight analysis allow one to obtain 2D spatial distribution of chemical elements in the examined object.

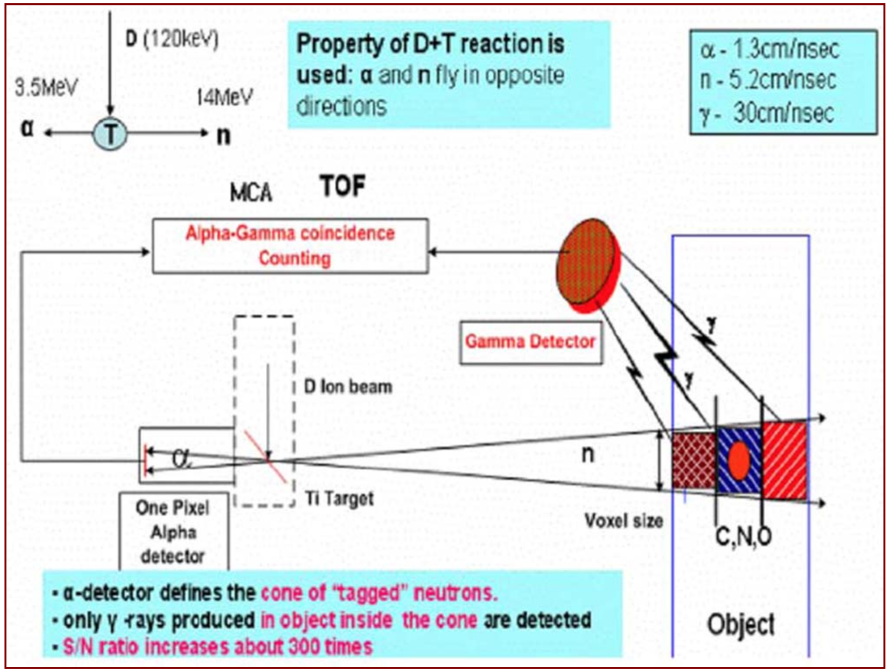


PFNA

Gozani 2005

Associated-Particle Imaging (API)

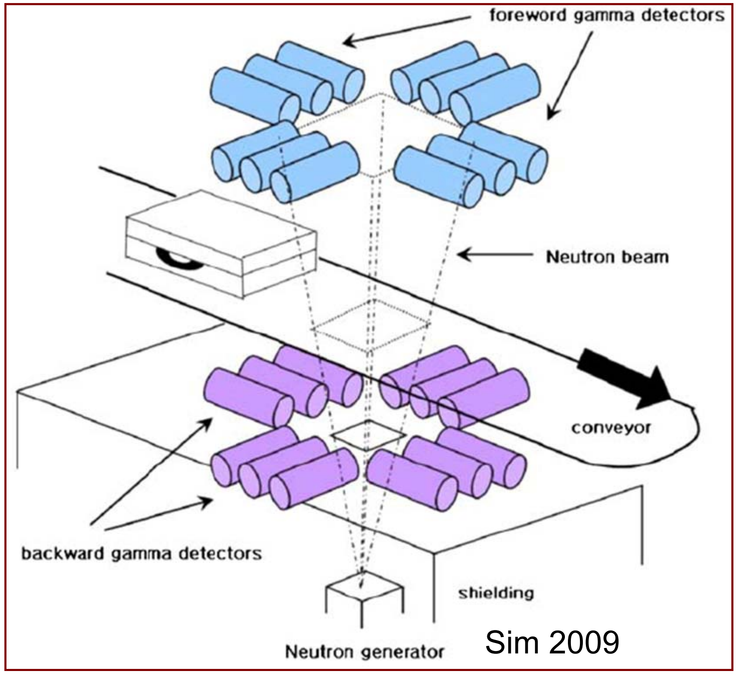
Nanosecond Neutron Analysis / Associated Particles Technique (NNA/APT): Use d(t,α)n to produce fast neutrons in portable neutron generators, mono-energetic neutrons (E = 14 MeV) and α-particles (E = 3 MeV) are emitted simultaneously in opposite directions. Tag *n* with alpha to discriminate secondary γ. Background γ-rays that are not correlated in time with "tagged" neutrons are rejected by the data acquisition system. Use of position sensitivity of the γ-detector and time-of-flight analysis allow one to obtain 2D spatial distribution of chemical elements in the examined object.



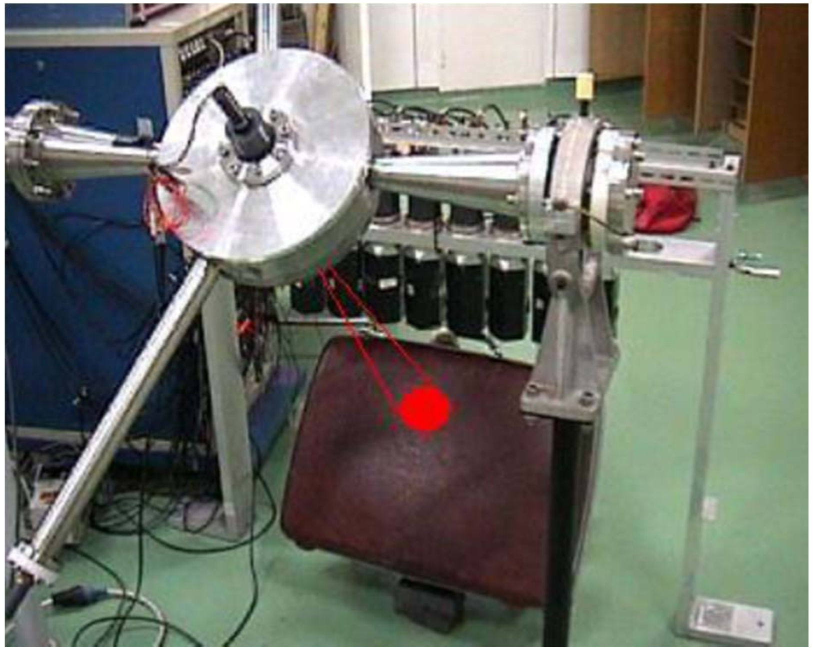
Property of D+T reaction is used: α and n fly in opposite directions

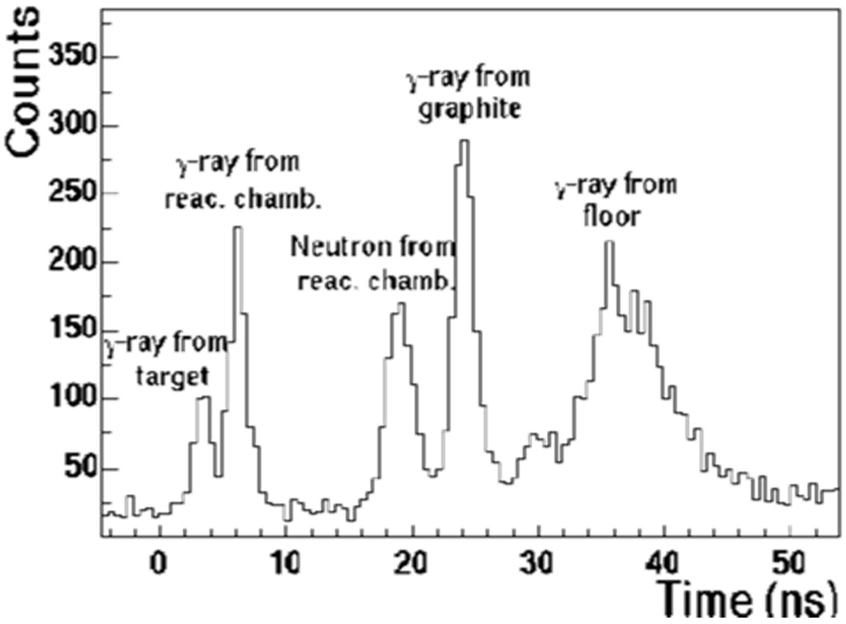
α - 1.3cm/nsec
n - 5.2cm/nsec
γ - 30cm/nsec

- α-detector defines the cone of "tagged" neutrons.
- only γ -rays produced in object inside the cone are detected
- S/N ratio increases about 300 times



Sim 2009




Counts
350
300
250
200
150
100
50
γ-ray from target
γ-ray from reac. chamb.
Neutron from reac. chamb.
γ-ray from graphite
γ-ray from floor
0
10
20
30
40
50
Time (ns)

Mulhauser

First Commercial Scanner – Nuctech AC6015XN

Needing improvement in order to be practical

Automated Cargo-Container Inspection System

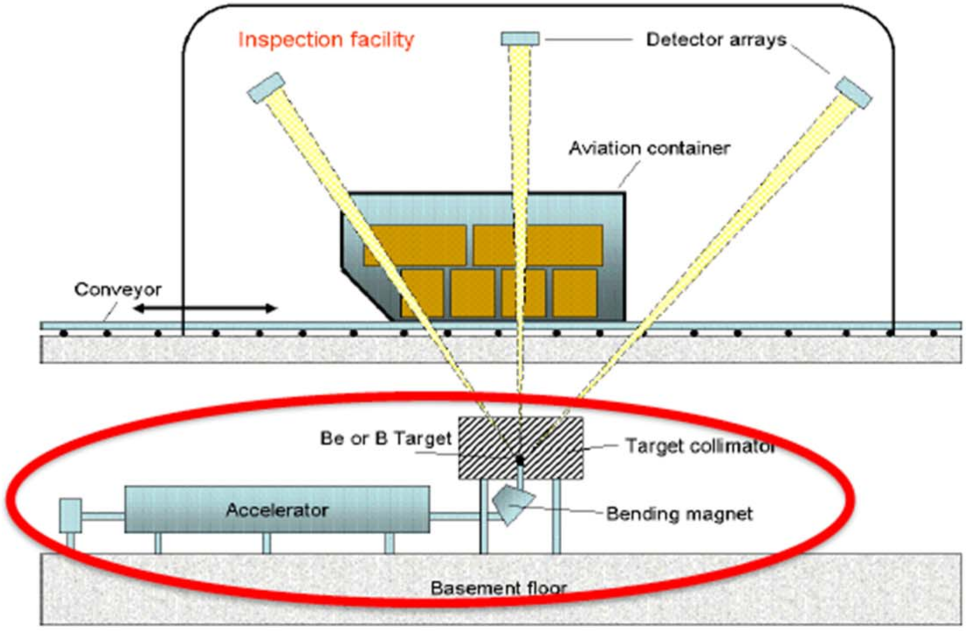
$^{11}B(d,n+\gamma)^{12}C$ – Deuteron Energy 3-8 MeV

4.43, 15.1 MeV γ-rays

Dual **D**iscrete **E**nergy
Gamma **R**adiografie
=> SNM detection

0-17 MeV neutron spectrum

Fast **N**eutron
Resonance **R**adiografie
=> Explosives detection



- (Semi-) Automatic Inspection
- Isotope specific Detection
- Combined Explosives & SNM Detection

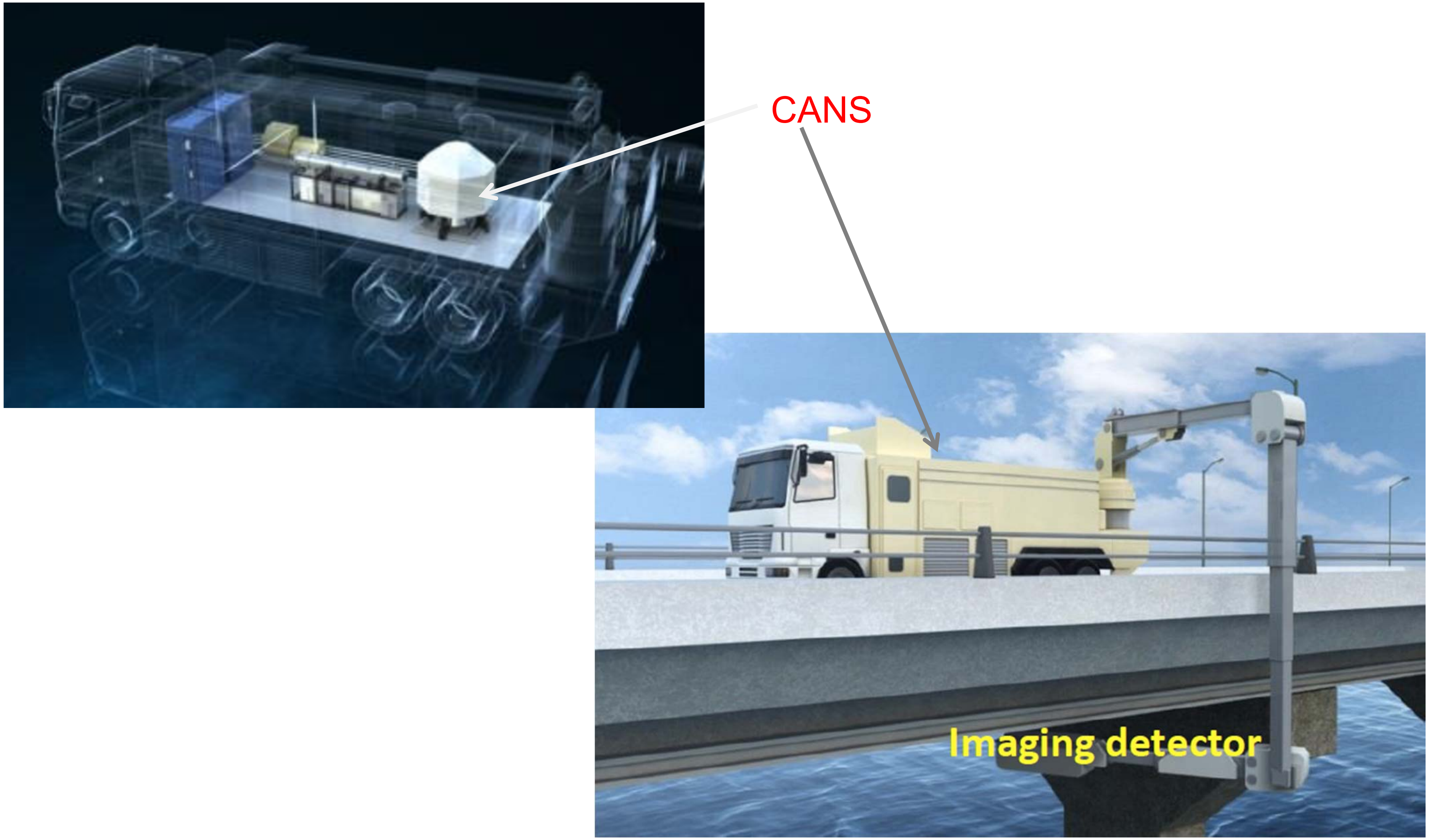
Bromberger (2015), UCANS-V

Landmine Detection: An Ongoing Effort

Mulhauser

Civil Engineering: Inspection of Large Infrastructure

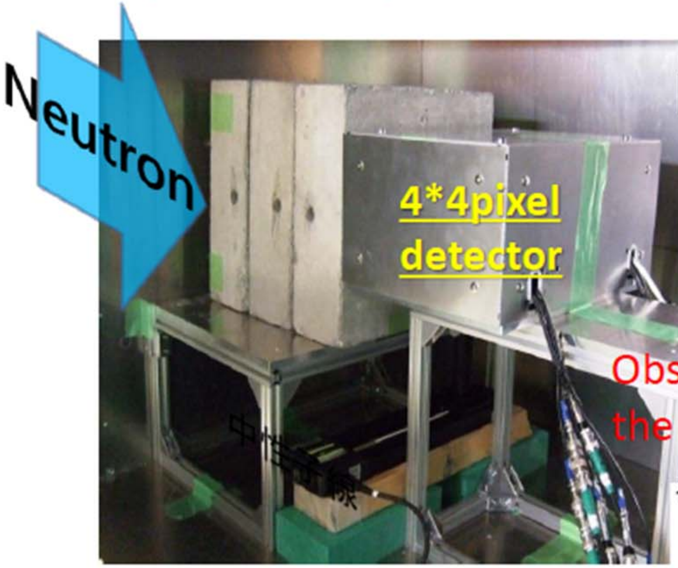
A Goal to be Fulfilled: Neutron Interrogation Using CANS, To Complement Other Methods

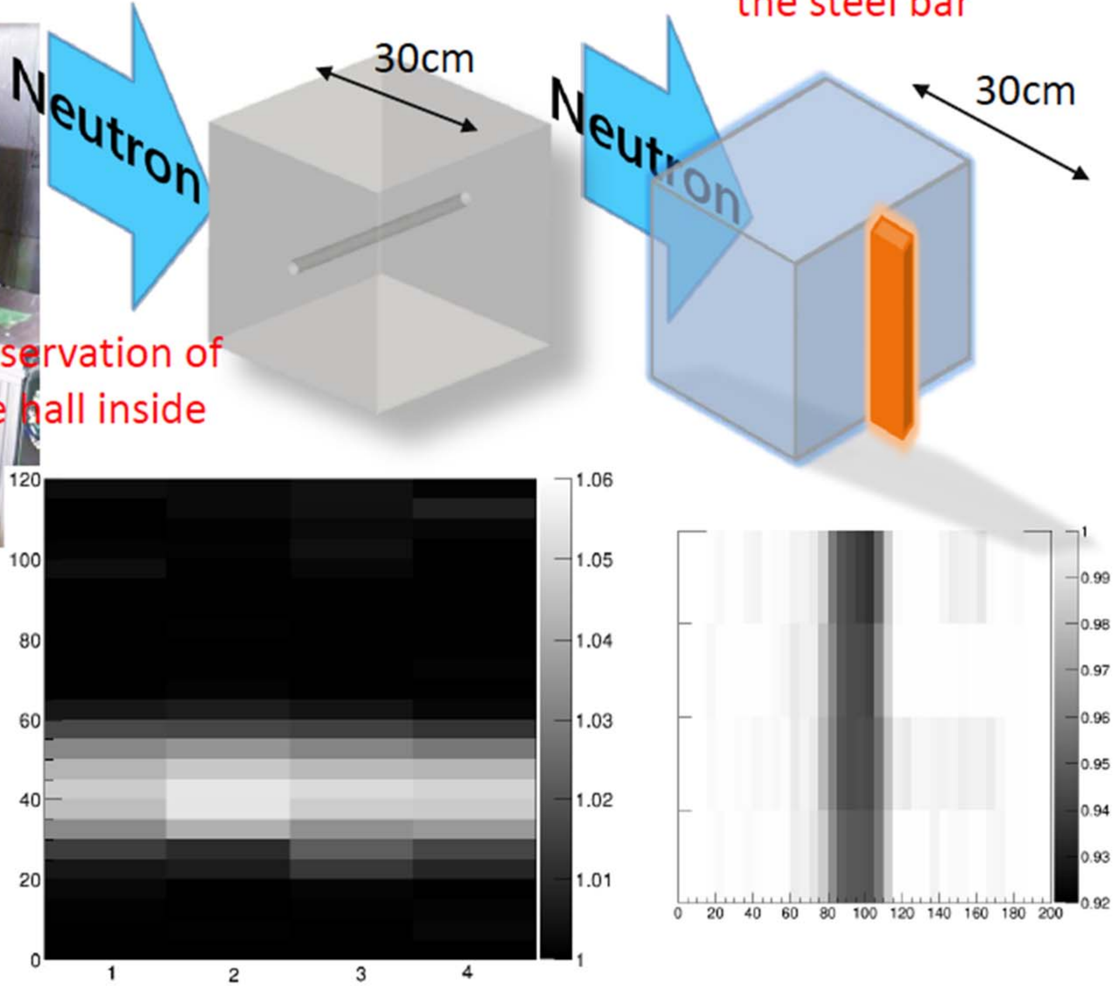


Otake (2013)

Fast neutron imaging through 30cm concrete block

(>1MeV) Non-destructive inspection





Observation of the hall inside

Observation of the steel bar

Proton linac

Proton energy: 7 MeV
Beam current: 11 μA (avg.)
Rep. rate: 20 Hz
Pulse width: 100 μs

Otake (2015), UCANS-V

Need Compact & Durable Neutron Sources for Well Logging

The Many Facets of Pulsed Neutron Cased-Hole Logging

☐The multipurpose RST service. Carbon-oxygen ratio, inelastic and capture spectra, sigma, borehole holdup, porosity, water and oil velocities, and borehole salinity are some of the measurements that can be made with RST equipment.

Advanced neutron generator design and fast, efficient gamma ray detectors combine to make a reservoir saturation tool that is capa of detailed formation evaluation through casing and more. Lithology determination, reservoir saturations and flow profiles are some of the comprehensive answers provided by this multipurpose tool.

Albertin (1996)

Nuclear Instruments and Methods in Physics Research A254 (1987) 563–569
North-Holland, Amsterdam

MOLECULAR SPECTROSCOPY OF n-BUTANE BY INCOHERENT INELASTIC NEUTRON SCATTERING

William B. NELLIGAN and David J. LePOIRE
Schlumberger – Doll Research, Ridgefield, CT 06877, USA

Chun-Keung LOONG and Torben O. BRUN
IPNS and MST, Argonne National Laboratory, Argonne, IL 60439, USA

Sow Hsin CHEN
Nuclear Engineering Department, MIT, Cambridge, MA 02139, USA

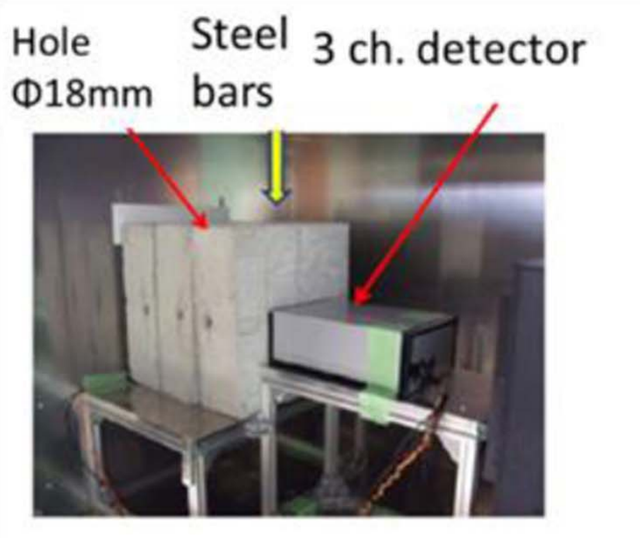
Received 24 July 1986

SPWLA 53rd Annual Logging Symposium, June 16–20, 2012

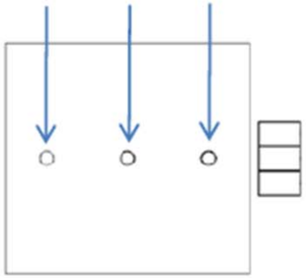
A NEW CAPTURE AND INELASTIC SPECTROSCOPY TOOL TAKES GEOCHEMICAL LOGGING TO THE NEXT LEVEL

R. J. Radtke, Maria Lorente, Bob Adolph, Markus Berheide, Scott Fricke, Jim Grau, Susan Herron, Jack Horkowitz, Bruno Jorion, David Madio, Dale May, Jeffrey Miles, Luke Perkins, Olivier Philip, Brad Roscoe, David Rose, and Chris Stoller, Schlumberger

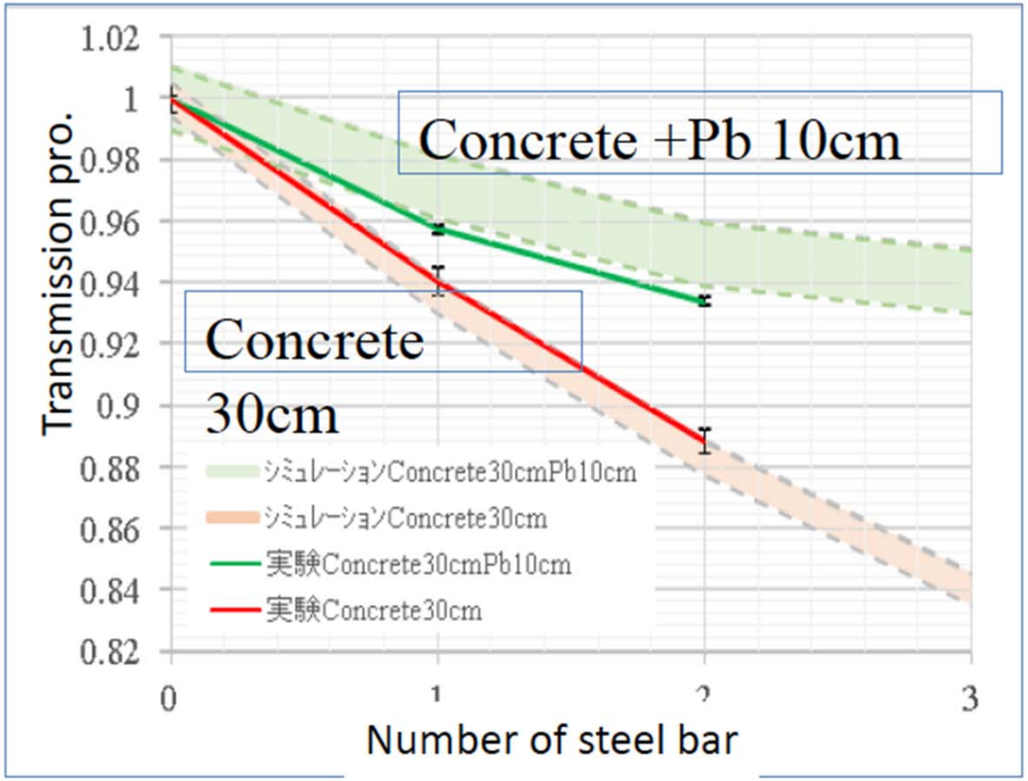
Success of observation difference of steel bar in the concrete



Insert ion bars
into concrete
0, 1, 2, 3

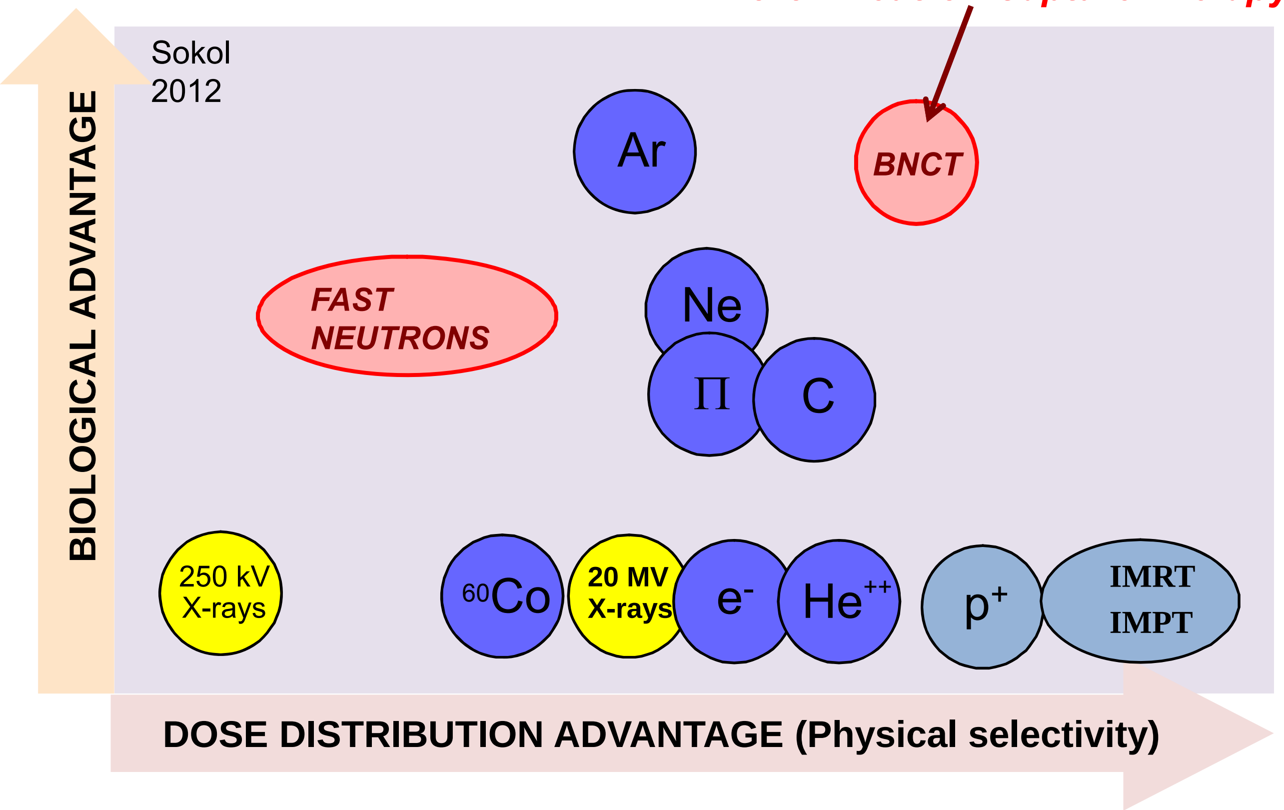


・comparison with the experimental results and simulation by GEANT4.



Otake (2015), UCANS-V

Neutron Therapy: Superior Biological advantage & Selectivity



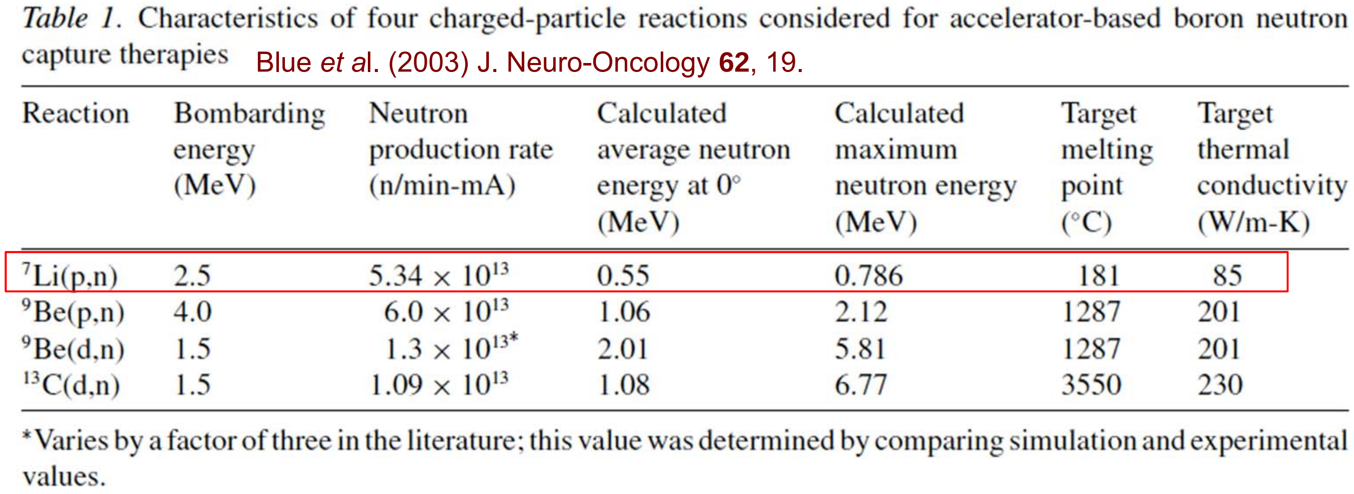
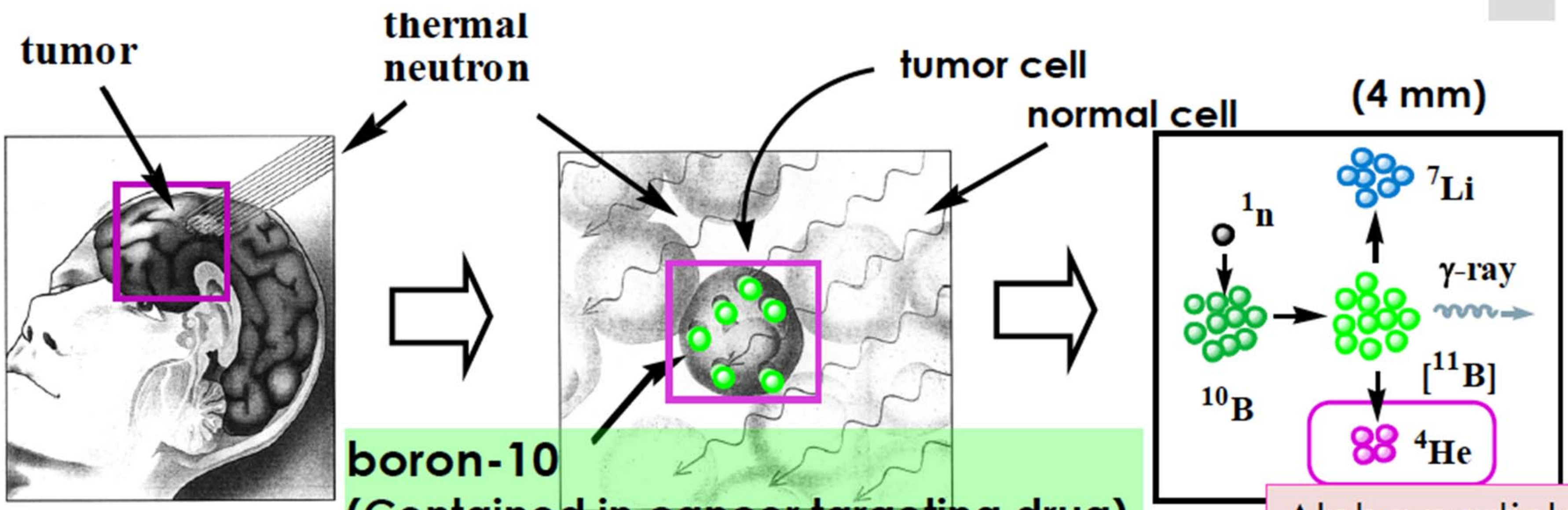


Table 1. Characteristics of four charged-particle reactions considered for accelerator-based boron neutron capture therapies Blue *et al*. (2003) J. Neuro-Oncology **62**, 19.

Reaction	Bombarding energy (MeV)	Neutron production rate (n/min-mA)	Calculated average neutron energy at 0° (MeV)	Calculated maximum neutron energy (MeV)	Target melting point (°C)	Target thermal conductivity (W/m-K)
^{7}Li(p,n)	2.5	5.34×10^{13}	0.55	0.786	181	85
^{9}Be(p,n)	4.0	6.0×10^{13}	1.06	2.12	1287	201
^{9}Be(d,n)	1.5	$1.3 \times 10^{13*}$	2.01	5.81	1287	201
^{13}C(d,n)	1.5	1.09×10^{13}	1.08	6.77	3550	230

*Varies by a factor of three in the literature; this value was determined by comparing simulation and experimental values.

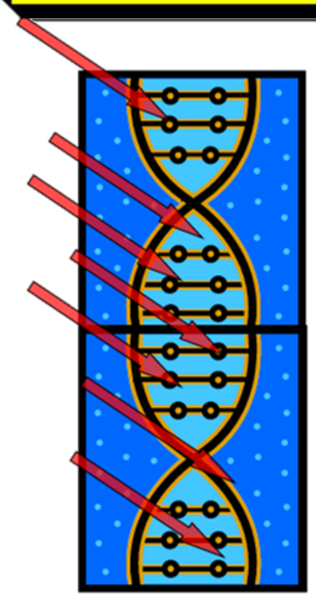


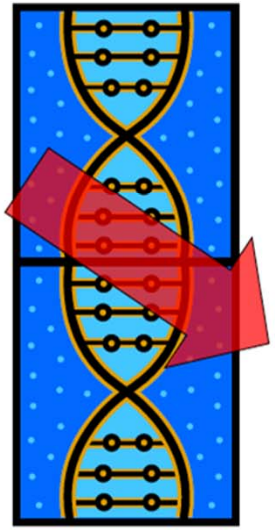
boron-10
(Contained in cancer targeting drug)

Alpha particle
Path length :10
micron

$$^{10}\mathrm{B} + {}^{1}\mathrm{n} \rightarrow [^{11}\mathrm{B}] \rightarrow {}^{7}\mathrm{Li} + {}^{4}\mathrm{He} + 2.79\ \mathrm{MeV}$$

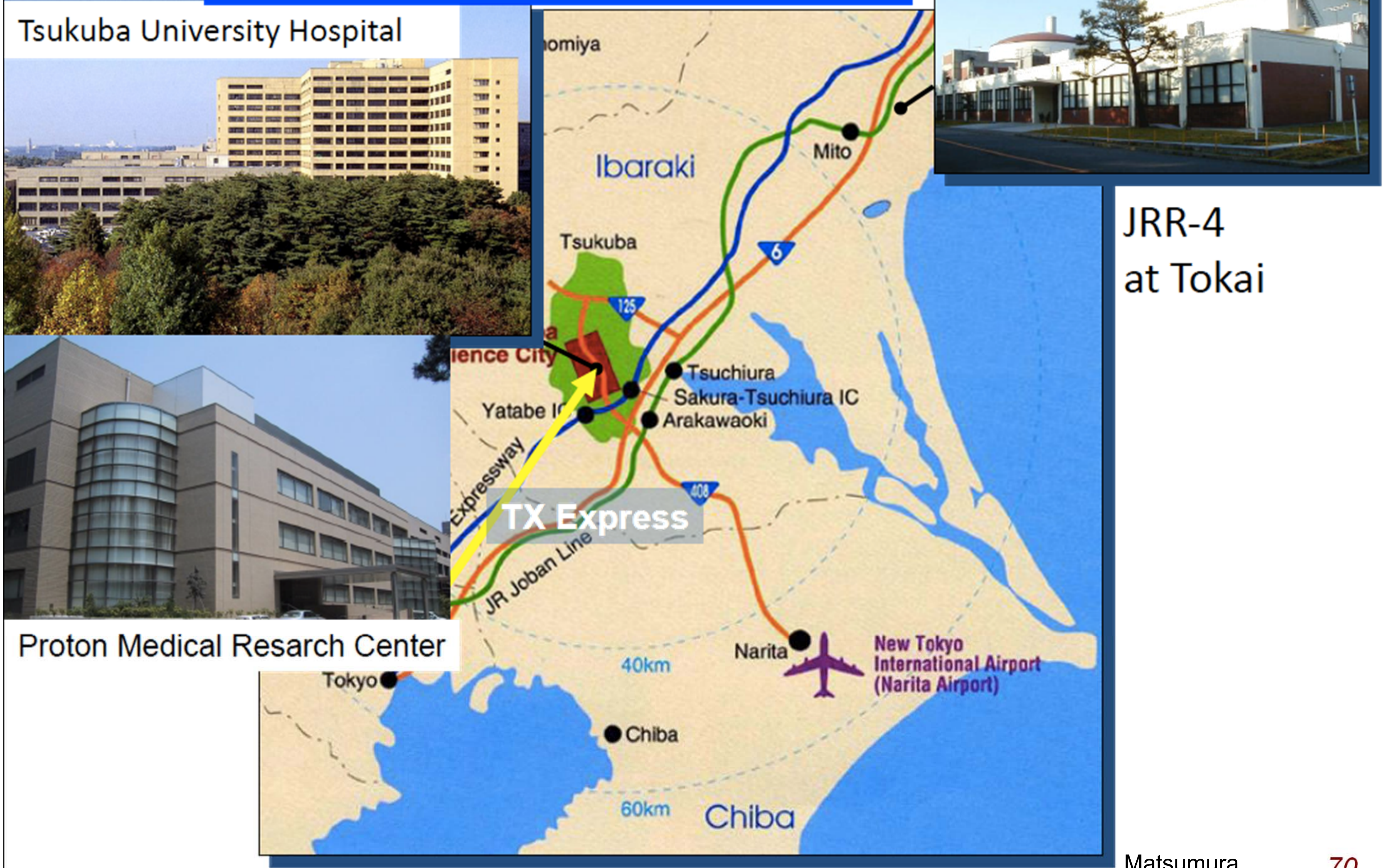
X-rays, ϒ-
rays, LE
protons





α particles & ^{7}Li nuclei from *boron neutron capture therapy* cut both DNA strands of the tumor cells

UNIVERISTY OF TSUKUBA BNCT GROUP



Tsukuba University Hospital

Proton Medical Resarch Center

JRR-4
at Tokai

Matsumura

Weekly Asahi, Special Issue on new treatment

Modalities (0ct,2010) issued on top page

最新治療
20

新

そ

週刊朝日
増刊号
定価650円

現代の最新治療2011

患者をどこまで救えるのか！

最新治療は実験的な側面がある。だから、最新は「最良」だとは限らない。しかし、「患者を苦しみから解放したい」と熱い志を持った医師たちは、日々、挑戦的な治療に臨んでいる。未来の標準治療の現場を歩いた。

写真／小暮誠、村上宗一郎、チェ・ドンス、谷本結利、山本倫子　取材／狩生聖子、岡谷りこ、竹本未代、美奈川由紀、石井悦子、安達まみ子　構成／坂田一裕

進化する放射線治療

ホウ素中性子捕捉療法

原子炉を利用した新しいがん治療

膠芽腫は脳腫瘍の一種。神経膠腫（グリオーマ、▼192㌻）の中でももっとも悪性度が高いとされている。この病気の治療に期待がかかるのが「ホウ素中性子捕捉療法」だ。患者の体内にあらかじめがん細胞にだけ集まる「ホウ素化合物」を投与する。その後、医療照射用の原子炉から発生させた中性子を患部に照射するとホウ素化合物との核反応が起こり、がん細胞を標的にして強力な放射線が発生する。

治療を実施する松村明医師（筑波大学病院副病院長）はこう話す。

「膠芽腫は脳の中に深く入り込んでいるので、標準的な放射線治療（X線）などでは再発例が少なくないため、効果的な治療法が期待されています。この病気では2年生存率が有効性の一つの指標になりますが、薬剤や照射法を工夫して実施した最先端の中性子捕捉療法では2年生存率が57・1%という結果（X線では21・1%）が出ています」

正常細胞には放射線がほとんどあたらないため、再発した場合も2度目の照射が可能。1度目の治療がX線や陽子線（▼170㌻）だった場合も症例によっては対象となる。現在、研究段階だが、頭頸部がんや皮膚がん、肝臓がん、肺がんなどにも実施されており、次世代のがん治療法として世界から注目されている。

照射室。壁の奥に炉心があり、ビーム孔から中性子が患部に向けて照射される

治療は茨城県東海村の日本原子力研究開発機構（原子力科学研究所）で実施している

中性子が水の中を通過するときに発生する青い光。「チェレンコフ放射光」と呼ばれる

松村 明 医師
筑波大学病院
脳神経外科教授
茨城県つくば市
天久保2-1-1
029-853-3900

■ホウ素中性子捕捉療法の治療の仕組み

ホウ素中性子捕捉療法の原理。正常細胞を傷つけずがん細胞を狙い撃ちにする

医師たちは原子炉稼働中の照射室に長時間入れないため、別室で照射の位置決めをする

Matsumura

Sample cases of BNCT Treatment (High effectiveness & preservatoin of normal tissue)

Prof.Kato,Osaka University

Recurrent Parotid Cancer

Pre BNCT

Recurrent tumor after Surgery, Chemotherapy and Radiotherapy. Skin erosion and infection is evident

After 2nd BNCT

Marked shrinkage of the tumor and regeneration of the skin

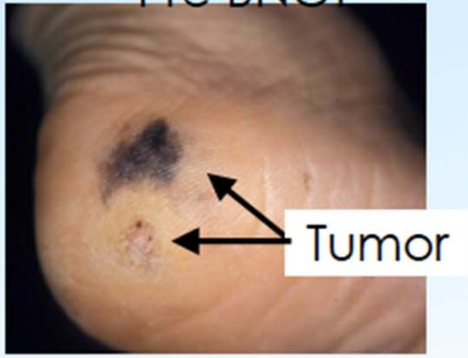
5M after 3rd BNCT

Complete cure by BNCT. The patient was alive 5 yrs without cancer recurrence

Malignant Melanoma at foot

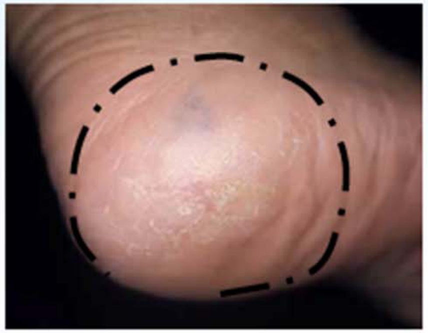
Corutsey of Kawasaki Medical University

Pre BNCT



3M after BNCT

6M after BNCT

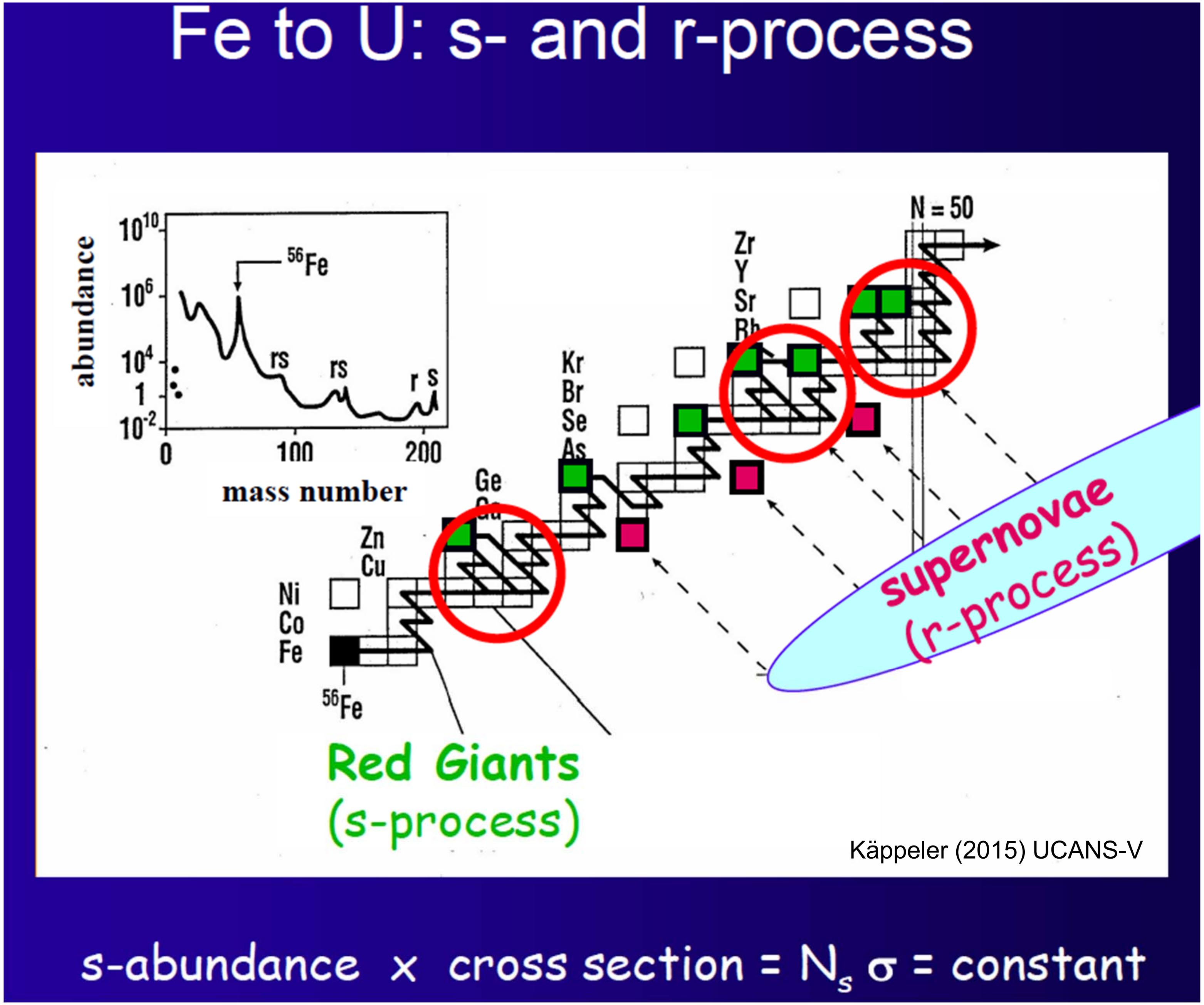


Fast Neutron Therapy (FNT)

- Fast neutrons damage cells through high linear-energy-transfer (HLET); kill cancer cells by cutting both cords of the chromosome helix.
- HLET reduces the numbers of treatment by >50% compared with other LLET therapies.
- Under hypoxic conditions (reduced oxygen supply) at the tumor tissue neutrons are more effective than x-rays.
- Currently FNT is only available at a handful facilities in Germany, Russia, USA and South Africa, mainly based on cyclotrons and reactors. Reactors need special beamlines to extract fast neutrons from the reactor core.

FRM-II

Other Applications: Nuclear Astrophysics, Nuclear Data



Fe to U: s- and r-process

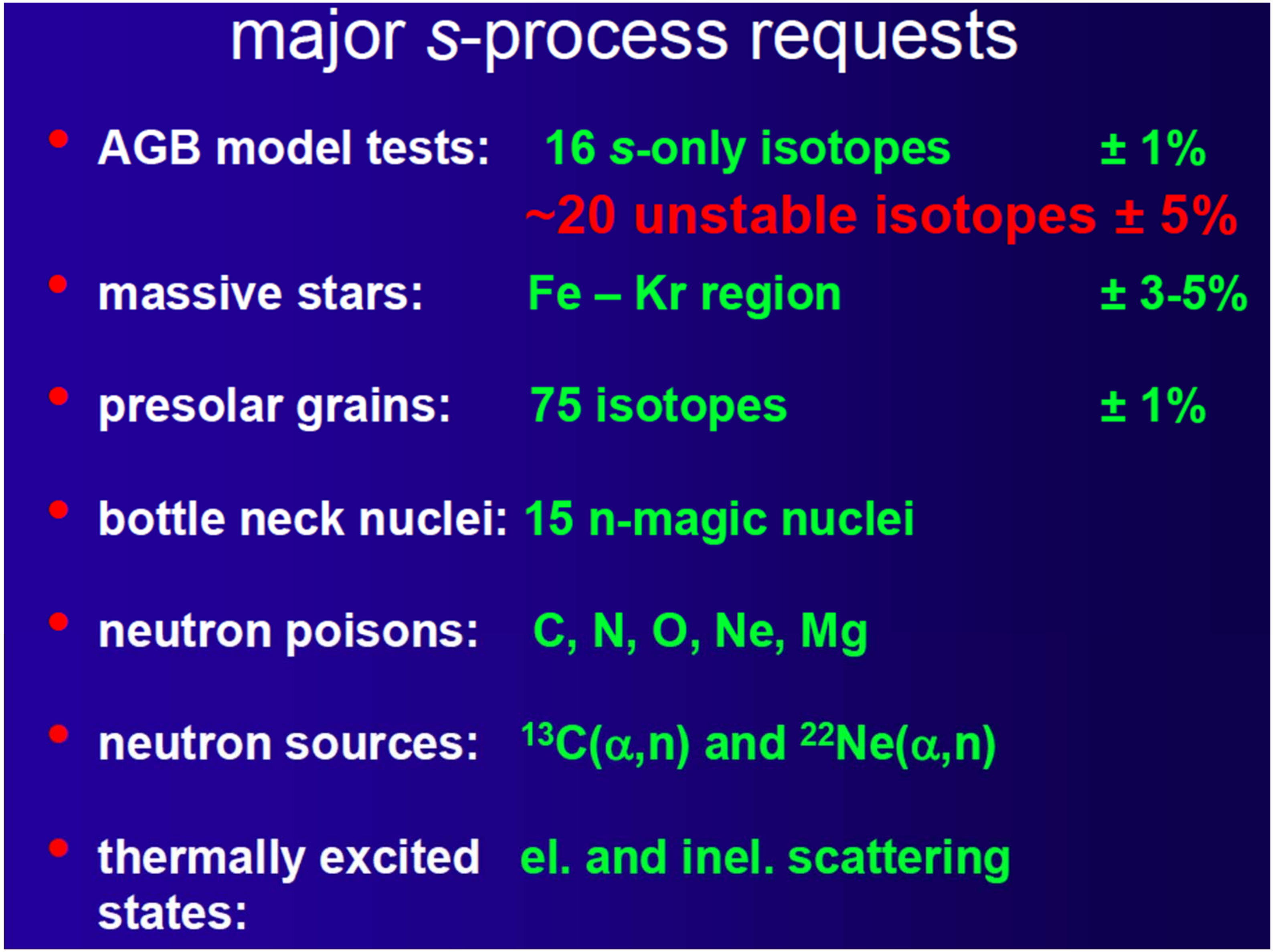
Red Giants
(s-process)

supernovae
(r-process)

Käppeler (2015) UCANS-V

s-abundance × cross section = $N_s\,\sigma$ = constant

The Neutron-related Needs Identified

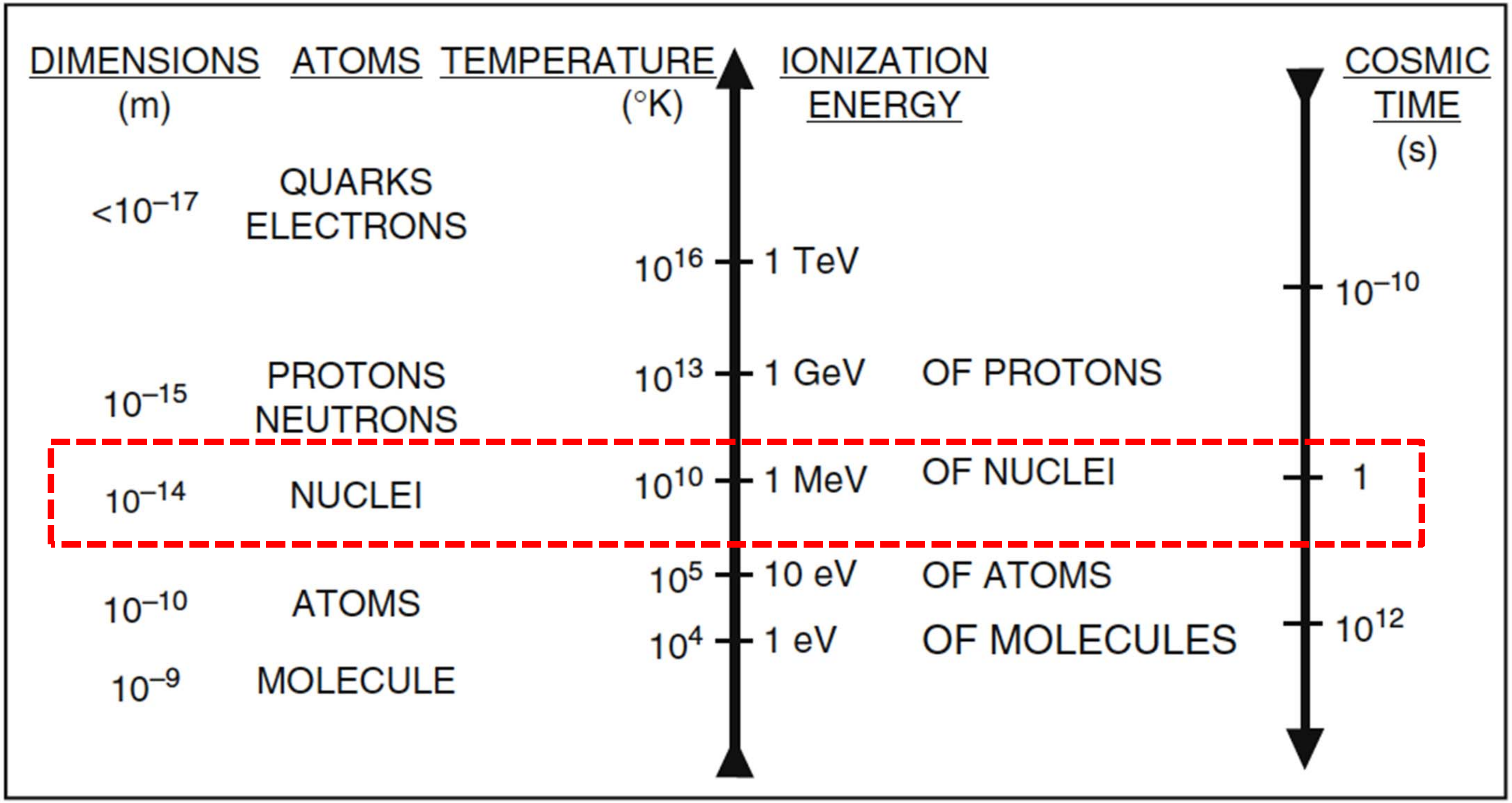


major *s*-process requests

AGB model tests:	16 *s*-only isotopes	± 1%
	~20 unstable isotopes	± 5%
massive stars:	Fe – Kr region	± 3-5%
presolar grains:	75 isotopes	± 1%
bottle neck nuclei:	15 n-magic nuclei	
neutron poisons:	C, N, O, Ne, Mg	
neutron sources:	$^{13}C(\alpha,n)$ and $^{22}Ne(\alpha,n)$	
thermally excited states:	el. and inel. scattering	

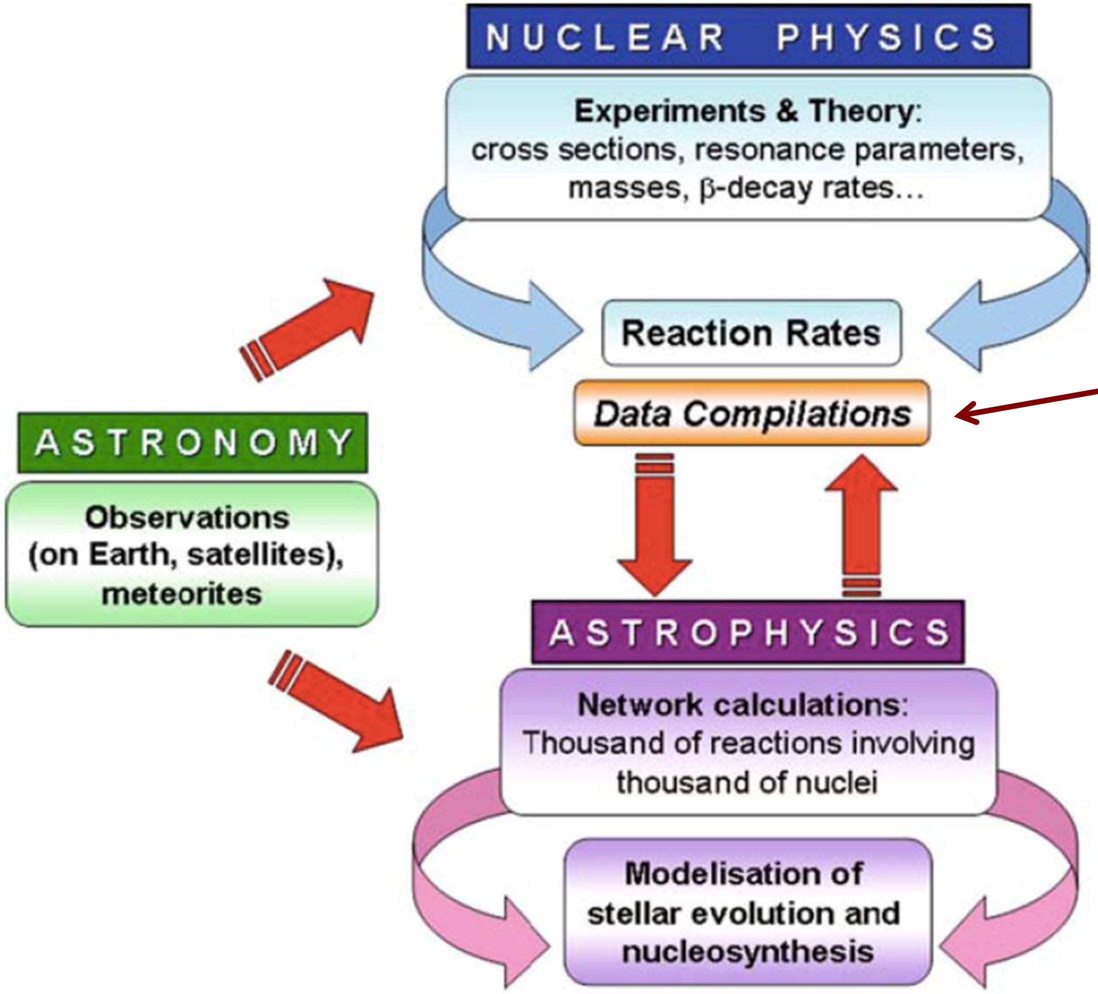
Käppeler (2015) UCANS-V

CANS provides neutrons of energies (~MeV) comparable to the temperatures of the sun and supernova explosion.



Reciprocity Theorem

$$\left(2I_x+1\right)\left(2I_X+1\right)\left(k_\beta\right)^2\sigma\left(\beta\rightarrow\alpha\right)=\left(2I_y+1\right)\left(2I_Y+1\right)\left(k_\alpha\right)^2\sigma\left(\alpha\rightarrow\beta\right)$$



NUCLEAR PHYSICS

Experiments & Theory:
cross sections, resonance parameters,
masses, β-decay rates…

Reaction Rates

Data Compilations

ASTRONOMY

Observations
(on Earth, satellites),
meteorites

ASTROPHYSICS

Network calculations:
Thousand of reactions involving
thousand of nuclei

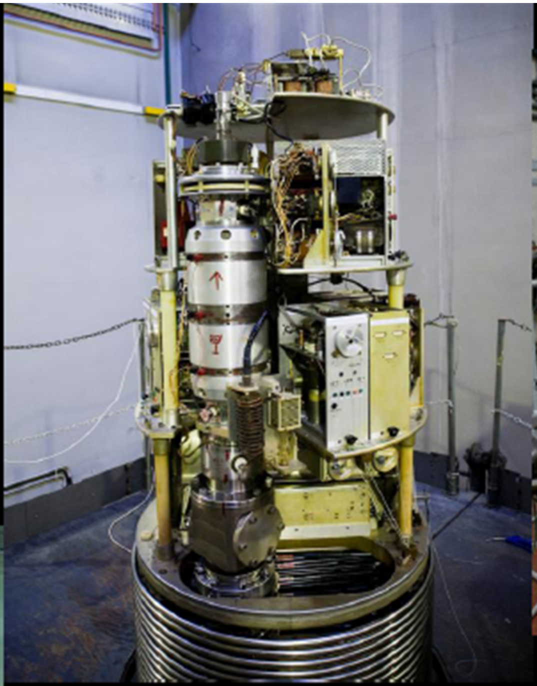
Modelisation of
stellar evolution and
nucleosynthesis

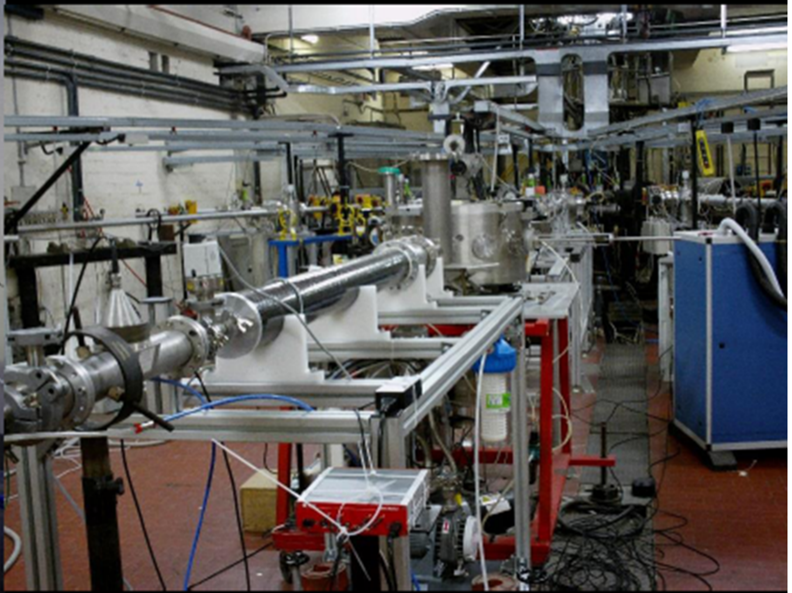
Cross sections obtained by CANS

Angulo

GELINA

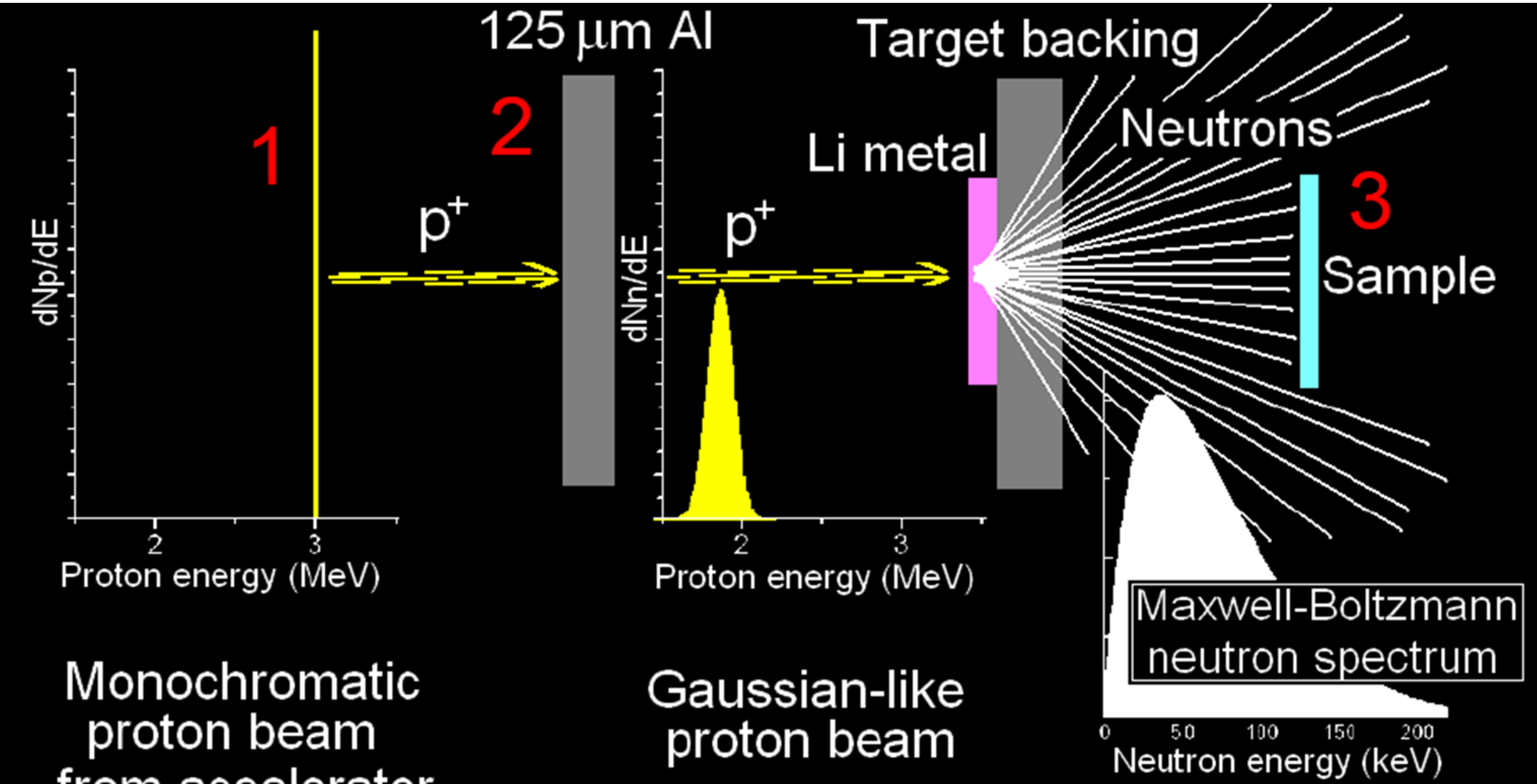
7 MV Van de Graaff at LNL
3 MHz pulsed proton beam, 300 nA





```
 145183 sweeps:  average     low     high   sigma
ampl(1)          0.268 V    0.025   1.200   0.323
sdev(1)           50.9mV      5.5   393.8    62.8
rise(1)         10.09 ns     0.05   49.98   10.86
fall(1)          8.70 ns     0.04   50.15    9.50
freq(1)       0.56185 Gs  0.02087 3.33333 0.30840
```

Mastinu (2015), UCANS-V



Monochromatic proton beam from accelerator

Gaussian-like proton beam

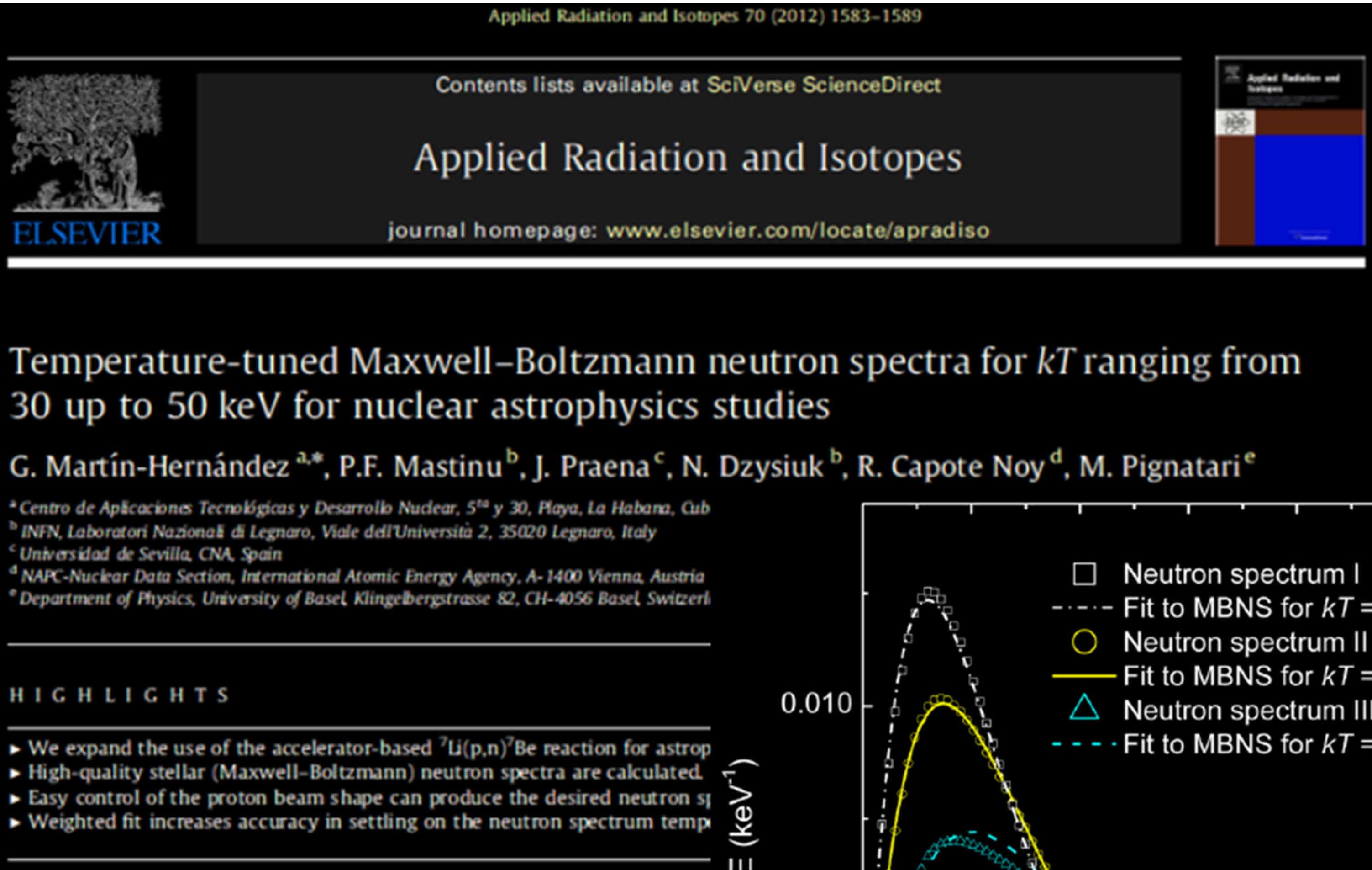
$$\frac{d^2Y}{d\Omega dE_n}(\theta,E_n) = N_{7_{Li}}\frac{d\sigma_{pn}}{d\Omega'}\frac{d\Omega'}{d\Omega}\frac{dE_p}{dE_n}\left(\frac{dE_p}{dx}\right)^{-1}$$

$$\left\langle \frac{d^2Y}{d\Omega dE_n}(\theta,E_n)\right\rangle = \frac{1}{\sigma_p\sqrt{2\pi}}\int_0^\infty e^{-\frac{(E_p-E_p^m)^2}{2\sigma_p{}^2}}\frac{d^2Y}{d\Omega dE_n}(\theta,E_n)dE_p$$

$$\frac{dY}{dE_n}(E_n) = 2\pi\int_0^{\theta_{max}}\left\langle\frac{d^2Y}{d\Omega dE_n}(\theta,E_n)\right\rangle \sin\theta\, d\theta \quad \longleftarrow$$

The neutron spectrum at the sample

Mastinu (2015), UCANS-V



Applied Radiation and Isotopes 70 (2012) 1583–1589

Contents lists available at SciVerse ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

Temperature-tuned Maxwell–Boltzmann neutron spectra for kT ranging from 30 up to 50 keV for nuclear astrophysics studies

G. Martín-Hernández [a,*], P.F. Mastinu [b], J. Praena [c], N. Dzysiuk [b], R. Capote Noy [d], M. Pignatari [e]

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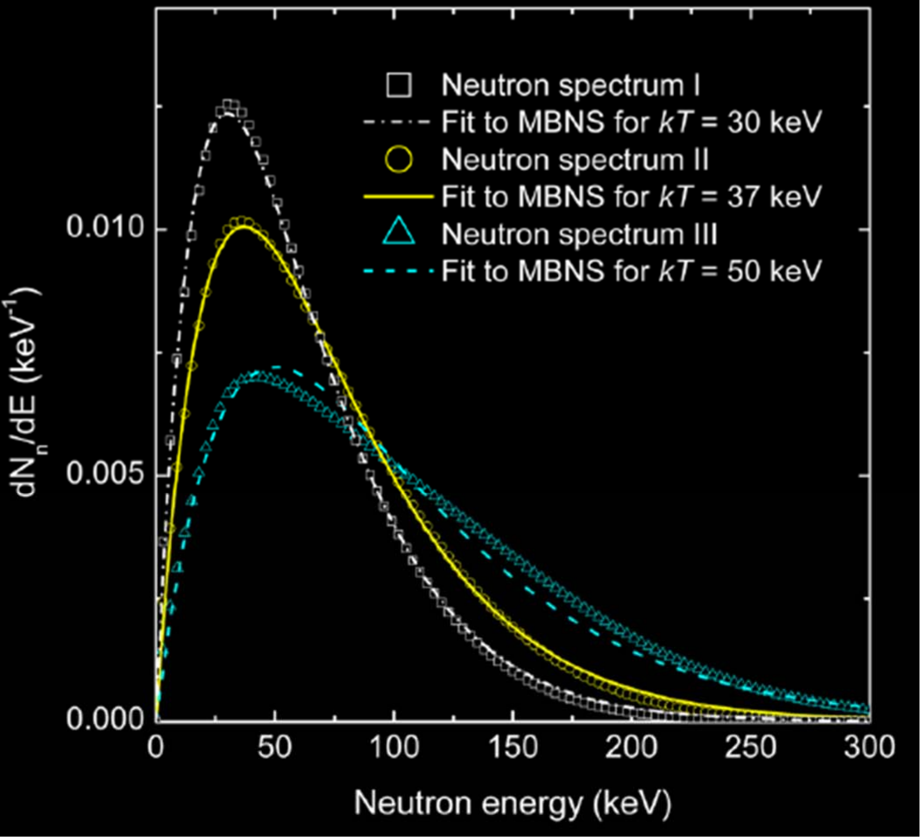
HIGHLIGHTS

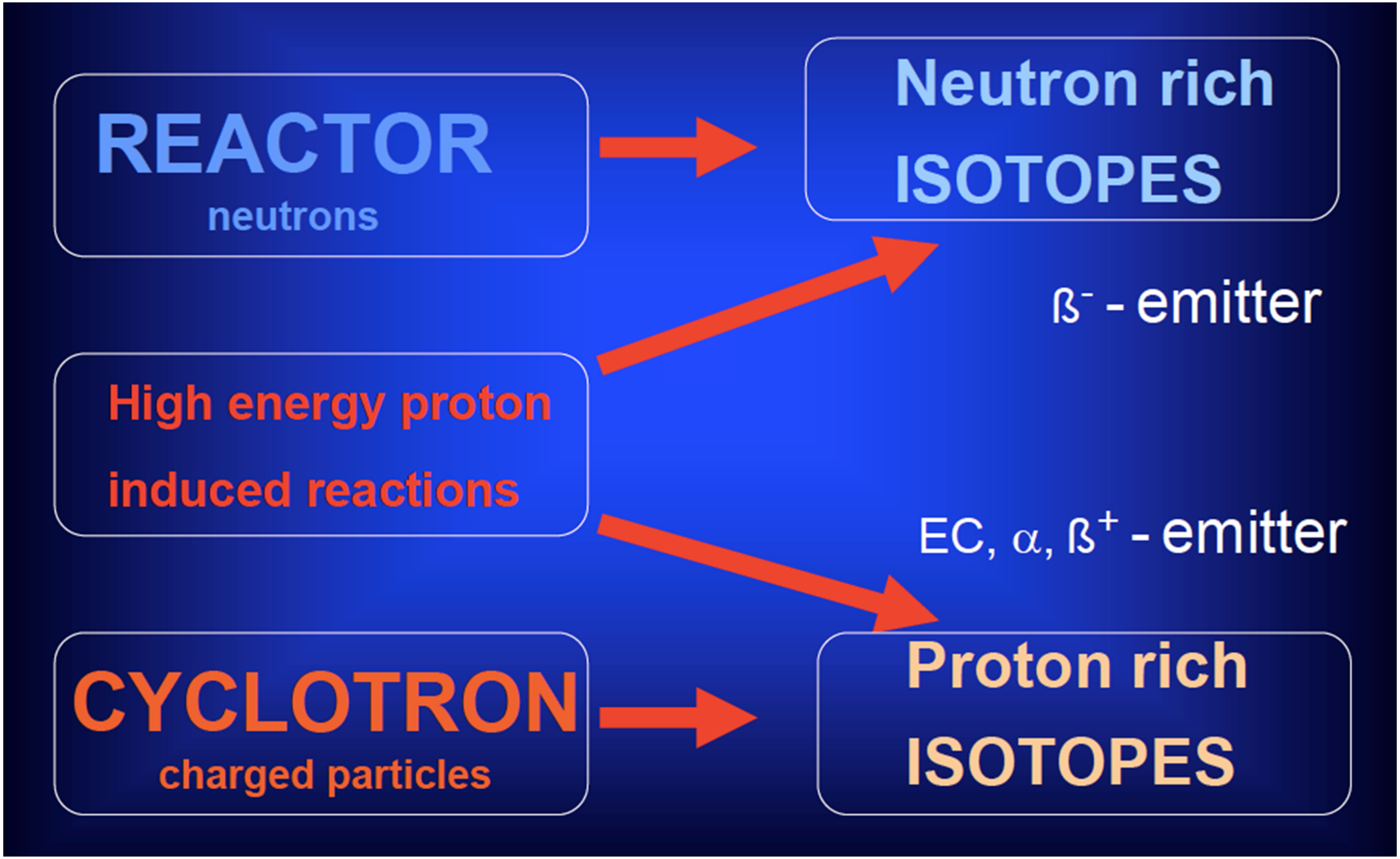
- We expand the use of the accelerator-based ^{7}Li(p,n)^{7}Be reaction for astrop
- High-quality stellar (Maxwell-Boltzmann) neutron spectra are calculated.
- Easy control of the proton beam shape can produce the desired neutron sp
- Weighted fit increases accuracy in settling on the neutron spectrum temp

Spectrum	E_p (keV)	E_p (keV) after foil	θ_{max} (degree)	kT (keV)	R^2	Neutron yield (n/pC)
I	4510	1795 ± 79	90	30	0.9995	4.3
II	4547	1865 ± 78	63	37	0.9998	16.4
III	4604	1973 ± 76	43	50	0.9975	37.7



Mastinu (2015), UCANS-V

Other Applications: Isotope Production



REACTOR

neutrons

High energy proton induced reactions

CYCLOTRON

charged particles

Neutron rich ISOTOPES

β^- - emitter

EC, α, β^+ - emitter

Proton rich ISOTOPES

Supply Problem of ^{99M}Mo/^{99}Tc Isotope for Medical Use

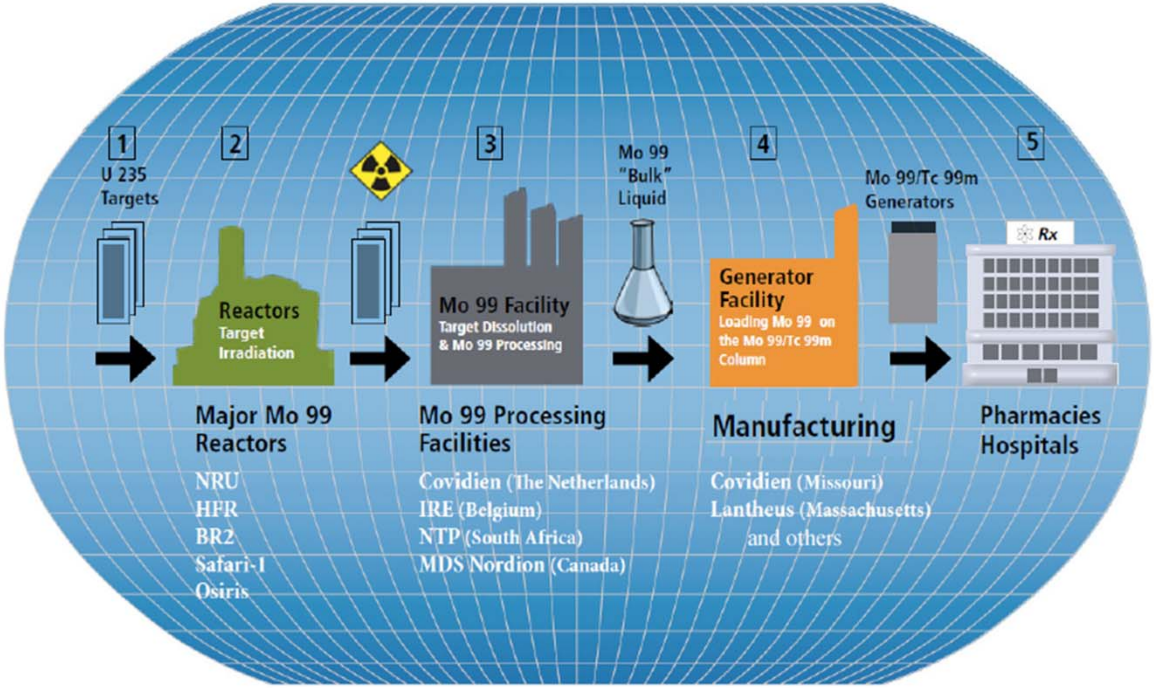


FIG. VII-1: Global supply chain of ^{99}Mo and subsequent utilization schematics. Source: www.covidien.com (October 2009)

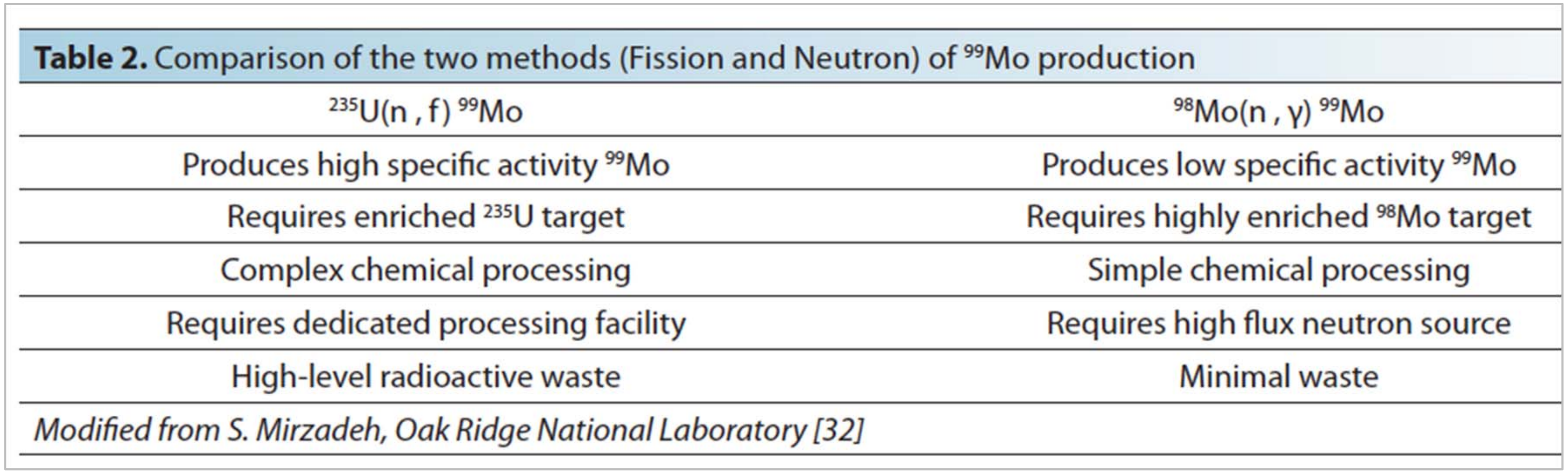


Table 2. Comparison of the two methods (Fission and Neutron) of ^{99}Mo production

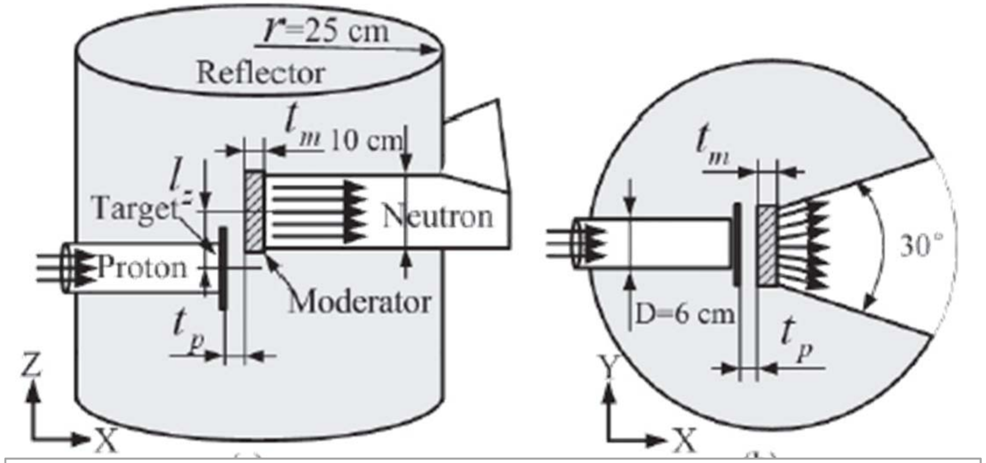
^{235}U(n , f) ^{99}Mo	^{98}Mo(n , γ) ^{99}Mo
Produces high specific activity ^{99}Mo	Produces low specific activity ^{99}Mo
Requires enriched ^{235}U target	Requires highly enriched ^{98}Mo target
Complex chemical processing	Simple chemical processing
Requires dedicated processing facility	Requires high flux neutron source
High-level radioactive waste	Minimal waste

Modified from S. Mirzadeh, Oak Ridge National Laboratory [32]

Conclusions about CANS Applications

- ✧ CANSs are cost-effective for development of neutronic instrumentation and enhancement of applied research across a broad spectrum of disciplines.

- ✧ Examples not shown here include continuing studies & testing of ***target & moderator design concepts*** and neutron ***beamline instrumentation*** in collaboration with large, high-power neutron sources.



CPHS target-moderator assembly. A good candidate for testing/solving technical problems, e.g., Ga cooling.

- ✧ So far CANS plays a strong role in education and in training users for preparing materials characterization studies at large user facilities, as demonstrated by the Japan Collaboration of Accelerator-driven Neutron Sources (JCANS).
- ✧ Expanding CANS' capabilities may be one of the options to maintain the growth of the user community in the neutron field.

Thank You

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Questions